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MODELLERING VAN DE EROSIEGEVOELIGHEID VAN DE BODEM IN HET SEMI-ARIDE GEBIED VAN KAMEROEN

Bepaling van de parameters van vlakte erosie voor het in kaart brengen van het risiko van bodemerosie door middel van GIS technieken in het Gawar gebied

MODELLING SOIL ERODIBILITY IN THE SEMIARID ZONE OF CAMEROON

Assessment of interrill erodibility parameters for mapping soil erosion hazard by means of GIS techniques in the Gawar area

By

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To my late daughter Inès Ndjeng

SAMENVATTING

De huidige landbouw- en veeteelt systemen zijn niet in staat om de behoeften aan voedsel in de semi-aride zone van Kameroen te bevredigen. Ofschoon vele oorzaken bijdragen tot deze onevenwichtigheid, is bodemerosie een belangrijke oorzaak van het voortdurend teruglopen van het areaal aan landbouwgrond en afnemende duurzaamheid van het land voor voedselproduktie. Veel erosie onderzoek is uitgevoerd, maar conserveringsprogrammas zijn vaak mislukt, waarschijnlijk omdat de modellen niet waren aangepast en overgenomen werden van gebieden met een verschillende ecologie en erosie processen. De conventionele modellen zijn voornamelijk gebaseerd op kleinschalig onderzoek dat grote gebieden beslaat. Maar spektaculaire schade door geulerosie verbloemt vaak de onderliggende aspekten van bodemerosie en hydrologie die plaatsvinden op het niveau van kleine percelen. De analyse van de processen die niet zichtbaar zijn op de schaal van een stroomgebied, zijn evenwel fundamenteel voor het verschaffen van concepten en kennis nodig voor efficiente ontwikkeling van onderzoek.
Deze situatie appelleert aan een begrip voor het lokale gedrag van erosie vóór het ten uitvoerbrengen van bodem- en water conserveringsplannen.

Onderzoek werd uitgevoerd in het Gawar gebied, in de semi-aride zone van Kameroen. Het gebied toont een verscheidenheid aan geomorphologische eenheden, bodemsoorten, akkerbouw systemen en bedrijfsvoering, en ontvangt de speciale aandacht van de regering en andere instellingen. Het algemene doel van het onderzoek was om het effect te onderzoeken van bodemerosie op gewas en veeteelt produktie. Om dit doel te bereiken moest aan drie specifieke doelstellingen worden voldaan:

- karakterizatie van de voornaamste bodems met betrekking tot hun erodibiliteit;
- begripvorming van de erosie processen, in het bizonder van vlakte erosie, en hun toepasbaarheid in vlakte-erosie modellen;
- onderzoek aangaande de mogelijkheid van het herstel van geerodeerde gronden voor gewasverbouw.

Drie ruimtelijke niveaus van onderzoek werden in aanmerking genomen:

(1) Op stroomgebied niveau: de bodemvariabiliteit en de verspreidingspatronen werden bestudeerd door middel van een conventionele bodemkartering, gebruikmakend van de geopedologische benadering en analyse van de bodem-landschap relatie.

(2) Op perceel niveau: de ruimtelijke verspreiding van de erosie verschijnselen werd bestudeerd voor het opstellen van bodem- en waterconserverings maatregelen aangaande erosie onderhevige gronden.

(3) Micro-perceel niveau: het onderzoek betrof de tijdelijke variatie in afstroming, bodemverlies en de daardoor veroorzaakte veranderingen in de configuratie van het bodemoppervlak door directe regenval en afstroming. Vijfentwintig lokaties vertegenwoordigend de voornaamste regionale bodemtypen (Lixisols, Vertisols, Planosols, Cambisols, Fluvisols en Leptosols) van het semi-aride gebied van noord Kameroen, ieder met verschillende erosie klassen, werden onderworpen aan kunstmatige regenval. Regenbuien (drie per perceel) van verschillende intensiteit en duur werden gesimuleerd over veldjes van 1x1 vierkante meter, gebruikmakend van een regenvalsimulator. De veldjes waren kaal en bewerkt met een hak. De methode hield uitdrukkelijk rekening met de faktoren die zowel de

afstroming alswel de sediment concentratie in detail bepalen. Monsters van materiaal veroorzaakt door directe regenval (splash) en door afstroming (runoff) werden ieder tien minuten genomen gedurende iedere gesimuleerde regenval. Ook werd de oneffenheid van het bodemoppervlak bepaald. Deze methode bestond uit het opmeten van de hoogte van het bodemoppervlak met een lineaal, uitgaande van een referentie basislijn die over het oppervlak werd gelegd, langs trajecten die vijf centimeter van elkaar lagen op de veldjes van 1x1 m. De oorspronkelijke micro-topografie werd opgenomen net na het ploegen, dat volgde op de eerste regenbui of voorbevochtigde regen, en metingen werden gedaan na elke gesimuleerde regenbui.

Verschillende benaderingen, inclusief numerische klassifikatie, statistiek en geostatistiek, werden toegepast. De tijdelijke en ruimtelijke variaties van de erosie indikatoren werden geanalyseerd door variogram modellering en kriging interpolatie. Hierdoor was het mogelijk een onderscheid te maken tussen gebieden van erosie en sedimentatie binnen elk experimenteel perceel. ILWIS, Excel, Variowin en Surfer programmas werden gebruikt voor de data opslag,-manipulatie en –analyse, en voor het vervaardigen van kaarten.

Huidige en voorafgaande erosie op stroomgebied niveau heeft wijzigingen veroorzaakt in de bodemprofielen van elk bodemtype. Deze veranderingen hebben aanzienlijke variatie veroorzaakt van de bodemeigenschappen en het landgebruik, die geleid hebben tot het vaststellen en beschrijving van drie erosie klassen binnen een gegeven bodemtype: 1) gering geerodeerde bodems, 2) matig geerodeerde bodems en 3) sterk geerodeerde bodems.

Erosie indikatoren tonen ruimtelijke afhankelijkheid op perceel niveau. De twee voornaamste geidentificeerde oorzaken van de variatie zijn: 1) de verschillen tussen de observatie punten binnen een perceel en 2) verschillen tussen de bodems van de percelen. De meeste erosie indikatoren vertonen transitieve (bolvormige en exponentiele) variogram strukturen op matig geerodeerde Lixisols, terwijl deze indikatoren op matig geerodeerde Vertisols een lineaire variogram struktuur vertonen. Dit verschafte aanwijzigingen voor het vaststellen van de beperkingen voor gewas ontwikkeling en voor het bepalen van passende bodem- en water conserverings methoden.

Op micro-perceel niveau werden korstvorming, denudatie en "micro-rilling" processen gekarakteriseerd. De interakties tussen de erosie parameters stonden de ontwikkeling van een "interrill" erosie model toe. Deze vlakte erosie (K) werd berekend middels twee modellen: 1) het Kinnell model en 2) een lokaal model. Berekende waarden voor vlakte-erosie verschilde per model. Bodemverlies en K waarden berekend door het lokale model vertoonden een hogere correlatie (R^2 = 0.706) dan de correlatie berekend door het Kinnell model (R^2 = 0.305). De K waarden zijn een funktie van de bodemeigenschappen gerelateerd aan de verschillende erosie klassen van de voornaamste bodemsoorten.

ABSTRACT

The current agricultural and livestock systems are unable to satisfy food requirements in the semiarid zone of Cameroon. Although many causes contribute to this unbalance, soil erosion is a main factor causing a continuing arable land shrinkage and decreasing the land resource sustainability. Many erosion studies have been carried out but conservation programmes often failed, probably because the models were not adapted and borrowed from areas with different environment and erosion mechanisms. Conventional models are mainly based on small-scale research covering large areas. But, spectacular damage by rill and gully erosion often hides the basic aspects of soil erosion and hydrology that occur at the level of very small plots. The analysis of processes not discernible at the field or watershed levels is yet fundamental to provide concepts and knowledge required for efficient development of research. This situation appeals for understanding local erosional behaviour before implementing soil and water conservation strategies.

A research was conducted in the Gawar area, in the semiarid zone of Cameroon. The area offers a variety of geomorphic units, soil types, cropping systems and management practices, and receives special governmental and non-governmental attention. The general research aim was to examine the effect of soil erosion on agricultural and animal productions. To reach this goal, three specific objectives had to be satisfied:

- to characterize the major soil types in terms of their erosion status;
- to understand the erosion mechanisms, in particular those of interrill erosion, and incorporate them in interrill erosion models; and
- to examine the possibility of rehabilitating eroded soils for crop production.

Three spatial levels of research were considered:

(1) Watershed level: Soil variability and distribution patterns were studied by means of conventional soil mapping, using the geopedologic approach and soil-landscape pattern analysis.

(2) Plot level: Spatial distribution of the erosion features was investigated to formulate soil and water conservation measures on eroding soils.

(3) Micro-plot level: The study examined the temporal variation of runoff, soil loss and resulting changes in soil surface geometry as affected by splash erosion and sheet wash. Twenty five sites representing the main regional soil types (Lixisols, Vertisols, Planosols, Cambisols, Fluvisols and Leptosols) of the semiarid area of northern Cameroon, with different erosion classes, were subjected to artificial rainfall. Rain showers (three per plot) were simulated over one-square-meter plots at different intensities and durations, using a field rainfall simulator. Plots were bare and ploughed with a hand hoe. The method allowed the explicit consideration of factors determining both runoff and sediment concentration in detail. Samples of splashed-off material and runoff were taken every ten minutes throughout each simulated rain. Soil surface roughness was assessed. The method consisted of measuring surface elevation points with a ruler, from a reference baseline downwards to the soil surface, along transects 5 cm apart, on 1m by 1m plots. The initial microtopography was recorded just after ploughing, following the first shower or pre-wetting rain, and measurements were taken after each simulated rain.

Several approaches, including numerical classification, classical statistics and geostatistics, were applied. The temporal and spatial variations of the erosion indicators were analyzed by variogram modelling and kriging interpolation. This allowed to distinguish between erosion and deposition areas within each experimental plot. ILWIS, Excel, Variowin and Surfer programs were used for data storing, manipulation and analysis, and for displaying maps.

At watershed level, current or past erosion has caused modifications that have affected the soil profiles within each soil type. These modifications have created considerable variations of the soil properties and land uses, leading to the identification and description of three erosion classes within a given soil type: (1) slightly eroded soils, (2) moderately eroded soils, and (3) severely eroded soils.

At plot level, erosion indicators show spatial dependence. Two main sources of variation were identified (1) from the differences between observation points within a plot and (2) from the soil-to-soil differences between plots. Most erosion indicators showed transitive (spherical and exponential) variogram structures on moderately eroded Lixisols, whereas most erosion indicators on moderately eroded Vertisols exhibited a linear variogram structure. This provided clues to determine the constraints to crop development and establish appropriate soil and water conservation measures.

At micro-plot level, crusting, denudation and micro-rilling processes were characterized. The interactions among erosion parameters permitted to develop a local interrill erosion model. Interrill erodibility (K) was calculated from two models: (1) the Kinnell model and (2) a local model. Calculated interrill erodibilty values varied according to models. Soil loss and K values from the local model correlated higher ($R^2 = 0.706$) than soil loss and K values from the Kinnell model ($R^2 = 0.305$). The K values were a function of soil properties related to different erosion classes of the major soil types.

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CHAPTER 1

INTRODUCTION

The semiarid zone of Cameroon is located between the latitudes 8° to 13° N and the longitudes 13° to 16° E. The climate is soudanian to sahelian, characterized by a short rainy season from May to September (Suchel, 1972). The average annual rainfall is 600 - 1000 mm, with heavy rainfalls concentrated in the July - August period. The mean annual temperature is high (27 to 30° C), with maxima in March - April. The typical geomorphic profile consists of mountains, piedmonts, peneplains, plains and valleys. Basalt, granite, trachyte and sandstone are encountered in highlands and piedmonts, gneiss and sand dunes in the peneplains. Plains and valleys consist of alluvial deposits.

Cambisols, Fluvisols, Leptosols, Lixisols, Planosols and Vertisols are the major soil classes found in the soudano-sahelian zone of Cameroon (Segalen and Vallery, 1962; Humbel and Barbery, 1974; Brabant and Gavaud, 1985). The average annual rainfall would seem to be enough to produce one or two crops per year, but rainfall showers are agressive and patterns are erratic, with frequent dry spells within the rainy season. Paulino (1986) and Upton (1987) reported that, in Subsaharean Africa, the food staples grew only at 1.3 to 1.7% a year, which is insufficient to keep pace with human population growth at 2.5 to 3.2%. The semiarid zone is the leading livestock area of Cameroon where cows, goats, sheep and donkeys are raised. The World Resources Institute (1988) reported that cattle population increased by 57% from 1974-76 to 1984-86, resulting in a need for fundamental changes in the existing production systems. Extensive cultivation and shifting cultivation are being replaced by intensive and sedentary agriculture without fulfillment of the requirements for such a type of agriculture, regarding for instance fertilizer use and soil conservation practices.

The farmers' attempts to maintain and/or to further increase production have led to overuse of arable lands, resulting in loss of soil fertility and increase in soil erosion. Farmers extended also agriculture to marginal lands or hardsetting soils called "Hardé" (meaning sterile soils in the local language), formerly used for grazing and fuel wood harvesting (Seignobos, 1991), which sometimes results into land use conflicts between agricultural farmers and animal husbandry farmers. Arable farming on marginal land is subjected to frequent crop failure, mainly because of inadequate soil moisture. The potential increase in production, resulting from the increased acreage of cropland, could be offset to a large extent by the loss of future productive capacity of the soils caused by water erosion (Young, 1976).

Intensified land use under existing systems may become self-destructive, because it results in increased crust formation, hardsetting, runoff production, soil erosion and desertification. As a consequence, the land resource base is shrinking and its productive capacity is diminishing. Meanwhile, the posed problem is that of how to give reliable advice to farmers or extension officers in order to curb current erosion on cultivated fields. The chances are that erosion might already be in advanced state before any action is taken. In practice, this means that the soil conservationist is faced with a problem of land reclamation rather than just conservation (Sanders, 1988). In this context, research on soil-water relationships for effective conservation and utilization of soil and water is urgent to support planners and extension workers in developing conservation strategies appropriate for the local conditions.

1.1 PROBLEM FORMULATION

Soil erosion is an environmental problem with effects distributed all over the earth's surface. As a result, maps are effective tools to portray the impact of soil erosion. Many soil conservation programs have been undertaken to counteract damages caused by erosion. Various soil loss prediction models have been developed and differ from one another according to their objectives and scales. However, most of them have not been effective in the tropics and subtropics where soil erosion is currently a severe problem affecting the productive performance of many land use systems at different scales. As a result, there is a persisting trend towards deterioration of the natural resources (soil, water and vegetation) due to human activities. Three main causes may contribute to the failure of modelling soil erosion in tropical and subtropical environments: (1) models do not represent the processes involved in soil erosion; (2) models reproduce correlations between rainfall and runoff specific to the data set and to the range of soil types; (3) the lack of calibration and extensive data requirements limit the application of the models in the tropics. Also, most of the soil conservation programs have not been effective because soil erosion studies concentrated only on the physical component of soil erosion. Soil erosion is a multidisciplinary study domain, which involves socio-cultural and economic aspects, as well as physical ones.

The current trend in erosion research in developing countries is a search for new locally-applicable solutions, instead of an attempt to adapt or modify imported methods (Hudson, 1996). Furthermore, efficient soil erosion studies should be conducted at different spatial scales, using various approaches and equipment. There are interactions and complementarity among different spatial scales of soil erosion. Therefore, the present research focuses on the variability of erosion parameters at three different spatial levels: the watershed level, the plot level, and the micro-plot level.

1.1.1 Research at watershed level

The research at watershed level deals with the variability of erosion indicators, which depend on the entire ecosystem including climate, soils and production systems. The indicators are used to point out the most serious environmental problems, to assess the severity of erosion, and to identify areas of high erosion risk.

In the semiarid zone of Cameroon, areas of high erosion risk have already been identify. But, there is still a scarcity of maps showing the current state of soil erosion. In addition, there are only few reliable quantitative measurements of soil erosion in relation to different factors and causes. Most available information is based on reconnaissance surveys. Moreover, observations frequently lack a standardized methodology or any systematic basis allowing to generalize conclusions. Such an information base may be of use in creating public awareness, but it is of little value in developing and implementing strategies to prevent or control erosion (Lal, 1988; Zageye and Runge-Metzger, 1992). The transformation of the current situation into a more acceptable future, by distributing scarce resources among multiple users and objectives to minimize the costs caused by soil erosion problems, still needs special emphasis. In addition, modern environmental model requirements are in contrast with the rapid expansion of soil erosion and the availability of data in developing countries in general and in the semiarid area of Cameroon in particular.

The quantity of data needed to assess erosion risks and support land use planning exceeds the capacity of a manual system, to effectively produce relevant information for decision making, and requires the implementation of a geographic information system. Understanding the interactions between different soil erosion factors and presenting the results in an easier way (map) should precede any planning, policy making or action.

1.1.2 Research at plot level

The study at plot level is approached within the interactive system soil-plant under the impact of the rain. It provides on-site indicators that are obtained from land husbandry. The research focuses on the physical problems of erosion to assess the effects of the existing agricultural practices and promote the use of efficient conservation and rehabilitation strategies.

Many erosion studies have been conducted at plot level in the semiarid area of Cameroon (Pontanier et al., 1984; Thebe, 1987; Seiny, 1990; Mahop et al., 1995; Nill et al., 1996). But little attention was given to the extension and distribution of erosion over the farm area. Erosion assessment is not an aim in itself; it should lead to soil and water conservation measures. For making recommendations on soil and water conservation, erosion rates alone do not help much. The site-specific erosion problems and their effects on crop yields must be known to initiate conservation measures. Each soil has its own characteristics in erosion development. Two soils may generate similar soil loss but, they may show differences in coverage and location of actual damage.

A plot scale shows erosion and deposition features, defined by type and intensity, along the relief, with respect to climatic conditions, soil characteristics, topography, land use and management. Such knowledge is a base for the evaluation of sustainable land use practices.

Likewise, knowledge on the rehabilitation of marginal soils can contribute to increase current and potential crop and animal productions.

1.1.3 Research at micro-plot level

Some attempts have been made to determine the susceptibility to erosion of the soils in the semiarid area of Cameroon (Pontanier et al., 1984; Thebe, 1987; Seiny, 1990; Mahop et al., 1995; Nill et al. 1996). But a systematic assessment of soil erodibility and a model to predict it from soil characteristics are still lacking. In soil conservation projects, it might be necessary to determine the erodibility of many different soil types, before investigating the effect of the soil management practices on this erodibility. The results may help conceive efficient measures on the basis of soil properties in relation to erosion when planning conservation systems.

The soil erodibility cannot be estimated simply on the basis of measurable or observable variables. It has to be determined experimentally for every individual soil body by making elaborate soil measurements in unit field plots (Wischmeier and Smith, 1978). Researchers in the tropics still have to establish appropriate methods for monitoring and estimating, precisely, soil erodibility in relation to rain and soil characteristics (Lal, 1981). To avoid expensive and time-consuming measurements of field plots under natural conditions, many researchers have tried to predict soil erodibility from the results of simple laboratory tests. These tests range from general analysis of physical, chemical and mineralogical soil properties to the determination of specific aspects of the physical behaviour of topsoil material (Bergsma and Kamphorst, 1985).

Many erosion studies mainly emphasize watershed and plot scales, where serious erosion features such as rills and gullies occur. However, spectacular damage by rill and gully erosion often hides the basic aspects of soil erosion and hydrology that occur at the level of very small plots. Erosion processes not discernible at the plot or watershed level are yet fundamental to provide concepts and knowledge for efficient development of research. There is a desire to develop models to present the processes at work in soil erosion and deposition. The recent trend in erosion prediction models emphasizes fundamental and hydrologically-based concepts, because hydrologic inputs are needed to drive the erosion equations (Foster, 1988; Foster, 1990). The research at micro-plot scale intends to contribute to the understanding of the fundamentals of elemental erosion processes by investigating temporal variations of runoff, soil loss and resulting changes in the soil surface geometry, as affected by splash detachment, sheet wash and the properties of the topsoil layer. An attempt to develop a simple interrill erosion model based on the mechanisms of detachment and transport of soil particles is undertaken.

The research approach shows interdependence among the three different spatial levels. The watershed level provides information on the systematic variability and distribution of areas of different degrees of erosion severity, which is a prerequisite for conservation strategies to control erosion at the plot level. The detailed erosion study at micro-plot level helps to acquire knowledge on the current basic erosion processes required to evaluate land use practices at the plot level. In return, the micro-plot (0.5 to 2 m^2) and the plot (500 to 2500 m^2) levels provide useful data to establish a comprehensive land use plan for soil conservation at the watershed level. Consequently, the research approach combines a large array of techniques, from conventional soil survey to geostatistics and geographic information systems.

1.2 THE OBJECTIVES

1.2.1 General objective

Rising human and livestock populations in the semiarid zone of Cameroon cause resource use practices that lead to soil erosion, declining crop yields and loss of the soil productive capacity. Despite impressive research achievements from developed countries, there seems to be a failure to get the message across to the farmers and policy makers in developing countries. Unfortunately, pressure for quick responses to urgent problems (population increase, poor agricultural practices and poverty) lead to high erosion rates, damaging the most basic of our natural resources: the soil.

The basic issue of soil erosion and its implications and consequences in the soil-water-plant system have oriented the study towards the general goal of contributing to better understanding soil erosion processes and promoting better soil erosion control in the semiarid area of Cameroon, where limited information is available on soil erosion.

1.2.2 Specific objectives

To reach the general goal, specific objectives have to be satisfied, such as:

(1) Investigating the influence of morphological, physical, chemical and mineralogical soil properties on hydrological and erosion processes;

(2) Estimating interrill erodibility of selected soils and relating it to morphological, physical and chemical soil properties;

(3) Monitoring changes in soil surface geometry as erosion occurs on ploughed lands;

(4) Determining on a field scale, the horizontal distribution of erosion features and interpreting the relationships between spatial variation of soil properties, crop characteristics, and erosion;

(5) Investigating the influence of land use and local knowledge on soil conservation measures;

(6) Producing an erosion susceptibility map of the main soils for preservation, protection and rehabilitation planning in agricultural lands.

The present research does not pretend to represent at micro-plot scale erosion processes that normally take place at plot scale and watershed scale. The interest of the research is twofold. Firstly, the research highlights at micro-plot level erosion phenomena not discernible at larger scales. Secondly, it intends to establish relationships between soil erosion at micro-plot scale and intrinsic soil properties, with other factors held constant by judicious experiment procedures. For practical reasons, a square meter plot is a useful surface area for measurements of runoff and soil loss under rainfall simulation experiments (Valentin and Casenave, 1988). Small plots provide basic concepts and knowledge required for efficient developmental research. Phenomena not discernible at the field or watershed levels, such as splash erosion, runoff generation, crust formation, aggregate stability or ponding time, can be studied in detail and with a great accuracy at micro-plot level. In fact, the plot size determines to a large extent the types of erosion processes that occur and the intensity at which they operate. Therefore, it is clear that small plots (a square meter) allow to determine the sediment sources as well as the amount of sediment output. Erosion in these conditions would then be classified as interrill soil erosion, whereas erodibility would be classified as interrill soil erodibility. Moldenhaur and Koswara (1968), De Ploey (1979), Meyer (1981), Poesen (1981), Savat (1981), Bergsma (1986), Bradford et al. (1987), Miller and Baharundin (1987), Truman and Bradford (1990), Kinnell (1991), Le Bissonnais and Singer (1993), Le Bissonnais et al. (1995), Sharma et al. (1995), Sutherland et al. (1996) and Römkens et al. (1997) conducted similar investigations on micro-plots, with the size varying from 30 x 30 cm to 100 x 100 cm.

The integration of the slope factor with the results of erosion obtained at micro-plot scale permits to predict the vulnerability or susceptibility of the studied soils to erosion at plot scale and watershed scale, with managerial factors, such as the crop factor and the practice factor held constant.

1.3 THESIS CONTENT OVERVIEW

After giving general information on the semiarid area of Cameroon and describing the importance of the study area in chapter 2, chapter 3 discusses the conceptual frame and research approach. It includes conventional concepts and opinions related to soil erosion, and the techniques used in assessing the complexity of soil degradation by water erosion. The justification of the research is also given.

Chapter 4 presents the methods and techniques applied in this research, including conventional soil survey, rainfall simulation experiments and map production. Several approaches used, such as classical statistics, numerical classification and geostatistics, are explained.

Chapter 5 gives basic information about the variability and distribution of the landscapes and soils found within the study area. Changes that occur in soil properties because of erosion are described. Chapter 6 deals with the variability and distribution of the farming systems under the influence of the environment at the watershed level. Variability and distribution of the land uses and land management practices according to erosion classes are described at the plot level.

The statistical and geostatistical analysis carried out on a grid-form, at micro-plot level and plot level, to assess the spatial variability of erosion features and incidental features, such as crop behaviour, are presented in chapter 9.

Integrating the results from chapters 5, 7, 8 and 9, chapter 10 analyzes the interactions among the interrill erosion indicators. Chapter 11 focuses on the elaboration of the local models of interrill soil erosion and interrill soil erodibility. Chapter 12 integrates the results from chapters 5, 6 and 11, and provides qualitative description and quantitative analysis of the different erosion susceptibility classes. The land use options for conservation planning are proposed in chapter 13. Conclusions obtained during the research are presented in chapter 14.

CHAPTER 2

DESCRIPTION OF THE STUDY AREA AND SURROUNDINGS

2.1 THE SEMIARID ZONE OF CAMEROON

2.1.1 General characteristics

Cameroon is located between the latitudes 2° to 13° N and the longitudes 8° to 16° E. It covers about 475000 km^2 and is bordered by the Equatorial Guinea Republic, Gabon and Congo in the south, the Centrafrican Republic and Chad in the east, and Nigeria in the west. The southwestern part of the country borders the Atlantic Ocean for about 400 km. The northern part borders the Lake Chad.

The geographic location of Cameroon, its diversity in geomorphology and soils, and its proximity to water bodies cause a diversity in ecological zones. Messerli and Baumgartner (1978) and Suchel (1988) derived five main ecological zones from the mean annual rainfall and mean annual evapotranspiration: evergreen rain forest, semi-deciduous rain forest, humid savannah, dry grass savannah and thornbush savannah (table 2.1).

Table 2.1 Characteristics of the main agroclimatic zones of Cameroon (Messerli and Baumgartner, 1978; Suchel, 1988)

Ecological zones	Mean annual rainfall (mm)	Mean annual evapotranspiration (mm) (*)
Tornbush savannah	200 – 300	2000 – 2400
Dry grass savannah	300 – 800	1700 – 2000
Humid savannah	800 – 1500	1500 – 1700
Semi-deciduous forest	1500 – 1800	1400 – 1500
Evergreen rain forest	1800 – 3600	1300 – 1400

(*): Evapotranspiration was measured (Piche and Colorado methods) and calculated (Blaney-Crddle, Thornthwaite and Penman).

The estimated population is 12 million inhabitants, irregularly distributed. Human activities have disturbed or changed the natural system equilibrium, for instance, from forest into anthropogenic savannah. Erosion is expected to be higher in humid areas than in dry or semiarid areas, but because of the lack of vegetation at the beginning of the rainy season, the erosion rate in the semiarid zone is important. That is why much attention is paid to soil erosion phenomena in the semiarid zone of Cameroon.

Administratively, the semiarid zone of Cameroon, also called North Cameroon, is composed of the North and Far-North Provinces (figure 2.1). Geographically speaking, it is situated between the latitudes 8° to 13° N and the longitudes 13° to 16° E (figure 2.1). The zone covers about 102,000 km^2, representing 1/5 of the national territory. Its population is estimated to 2.8 million inhabitants, which represent 30 % of the total national population. The population is irregularly distributed (Roupsard, 1987) (figure 2.2).

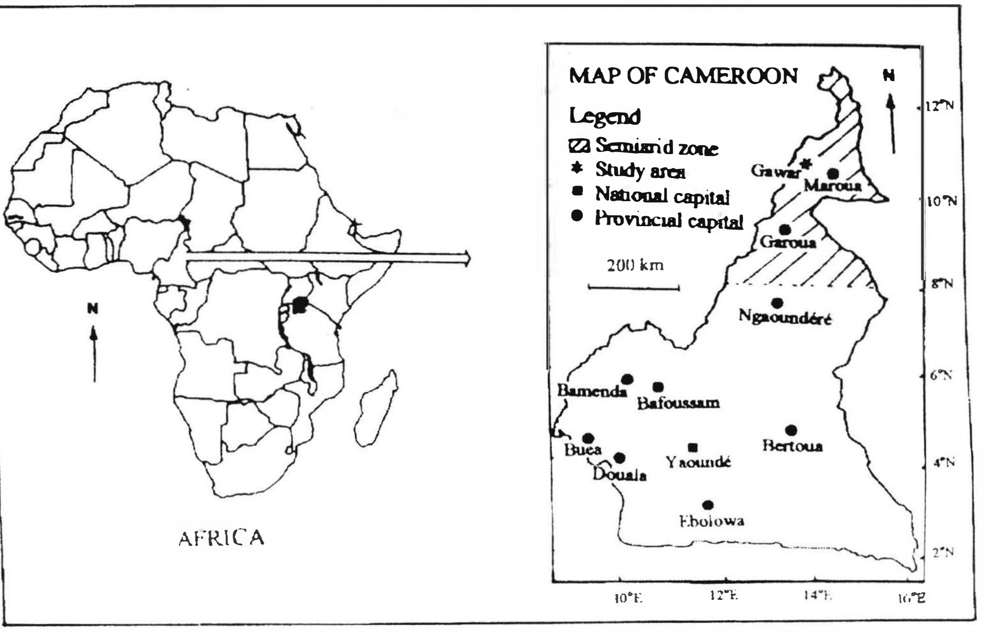


Figure 2.1 Location map of the semiarid zone of Cameroon

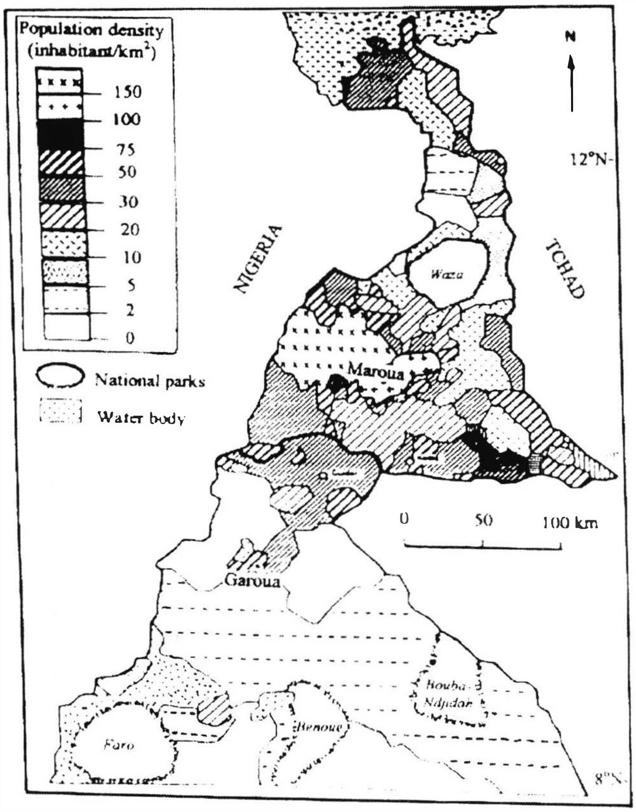


Figure 2.2 Population density distribution of North Cameroon (Roupsard, 1987)

2.1.2 Climate

Works done by Genieux (1958), Suchel (1972), Dubief (1977), Olivery (1986), Suchel (1986), Seiny (1990), Nill (1993), Boli (1996) and Mahop (1996) show that the climate in Cameroon is determined by tropospheric circulation characterized by the yearly oscillation of a zone of low pressure along the Equator, called the "Intertropical Convergency Zone". It follows the apparent movement of the sun with an one-month delay. The phenomenon, associated with cloudiness and rainfall, is restricted to a front towards which the winds converge and which is called the "Intertropical Front" (ITF). The ITF reaches its northern limit (20° N) in July and its southern limit (4° S) in January. This front demarcates to the south a maritime equatorial air mass, which is warm and moist, from an air mass north of the front arriving from the northeast or east, which is hot and dry. The hot wind, called "Harmattan", blows from north to south at its origin, but turns gradually towards the east and increases in strength with decreasing latitude. The displacement of the ITF causes seasonality: a dry period alternates with a rainy period, giving rise to a monsoon climate.

In the semiarid zone of Cameroon, the monsoon climate is of soudano-sahelian type, characterized by two contrasting seasons: a short rainy season from May to September and a long dry season from October to April (figure 2.3). Rainfall decreases towards the north (figure 2.4), originating four agroclimatic zones: soudanian, soudano-sahelian, sahelian and modified soudano-sahelian.

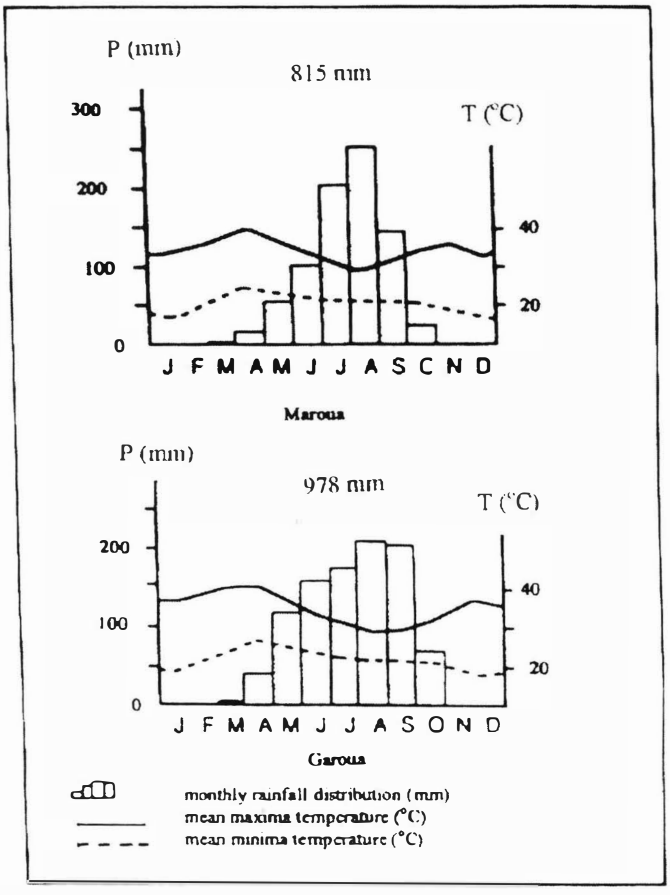


Figure 2.3 Ombrothermic diagrams for Maroua and Garoua (Suchel, 1972)

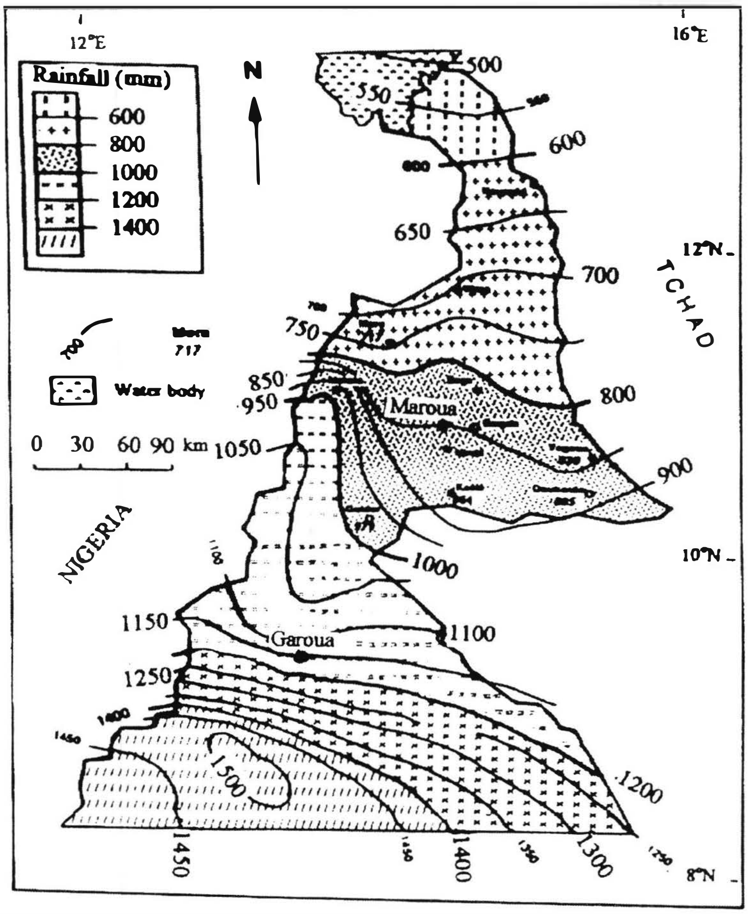


Figure 2.4 Spatial distribution of rainfall (Brabant and Gavaud, 1985)

(1) Soudanian agroclimatic zone

The soudanian agroclimatic zone occupies the area between the latitudes 8° and 10° N. The rainy season goes from May to September. The annual rainfall varies between 1000 and 1200 mm, and occurs in approximately 80 days. Highest daily and monthly temperatures are recorded around Garoua city. The average annual temperature is about 28°C. This agroclimatic domain occurs in the Bénoué basin.

(2) Soudano-sahelian agroclimatic zone

The soudano-sahelian agroclimatic zone is located between the latitudes 10° and 12° N. The rainy season goes from June to September. The average annual rainfall varies between 700 and 1000 mm, and occurs in about 70 days. The average annual temperature is 27°C. This agroclimatic zone is the domain of piedmonts, peneplains and plains.

(3) Sahelian agroclimatic zone

The sahelian agroclimatic zone is encountered between the latitudes 12° and 13° N (Lake Chad border). The rainy season is shorter, the annual rainfall varies between 500 and 700 mm, and occurs in approximately 60 days. The Harmattan wind is more pronounced here.

(4) Modified Soudano-sahelian agroclimatic zone

This agroclimatic zone is found in the highlands of the soudano-sahelian area, between 750 and 1200 m elevation. The dry season shortens and the temperature decreases with increasing altitude. The average annual rainfall is about 1000 mm and occurs in approximately 70 days.

The common features of the four agroclimatic zones encountered in the semiarid area are as follows:

- short rainy season, with heavy rains concentrated in July and August;
- erratic rainfall pattern with frequent dry spells within the rainy season;
- a relatively high average annual temperature with maxima in April and May; the lack of rain is accompanied by a high evaporation power of the atmosphere;
- relative humidity of the air variable between 10% (dry season) and 90% (rainy season);
- solar duration variable between 8 and 10 hours per day, except during the rainy season;
- dominant wind type "Harmattan", characterized by dryness, strong thermic turbulence and large content of air-borne dust particles; it gives rise to the so-called "dry haze" during the dry season.

2.1.3 Geology

Works done by Koch (1959), Segalen (1962), Sieffermann (1963), Sieffermann and Martin (1963), Schwoerer (1965) and Pouclet and Durand (1984) show that, at the beginning of the Cretaceous, strong tectonic activity caused the collapse of the Bénoué valley as a graben bordered by sharp escarpments. Detrital and laguno-lacustrine sediments, sandstone and clayey materials were deposited. Horizontal continental and fluvial sand layers filled the Bénoué valley. The basement was affected by graben and horst formation. Intensive volcanic activity occurred during the lower Cretaceous. During the middle Cretaceous, detritic deposits continued filling the valleys and covering low plateaus. Clayey and arkosic materials were deposited. During the upper Cretaceous, the absence of deposition during long dry periods allowed the formation of laterite on sandstone. During the Tertiary and Quaternary, basaltic deposits covered the substratum. River courses built up alluvial terraces. During the late Quaternary, valley bottoms were formed. Sand dunes corresponding to an extension of the Lake Chad (lacustrine transgressions) marked the Paleolithic period (about 8000 BC). These sand dunes were reworked by the wind during a desertic phase, that preceded a new extension of the Lake Chad at the end of the Paleolithic.

The main geologic material of the substratum in North Cameroon is a granito-gneissic complex, covered by fluvial and lacustrine deposits. Some other formations, namely sedimentary and metamorphic rocks, are spread over the area (figure 2.5).

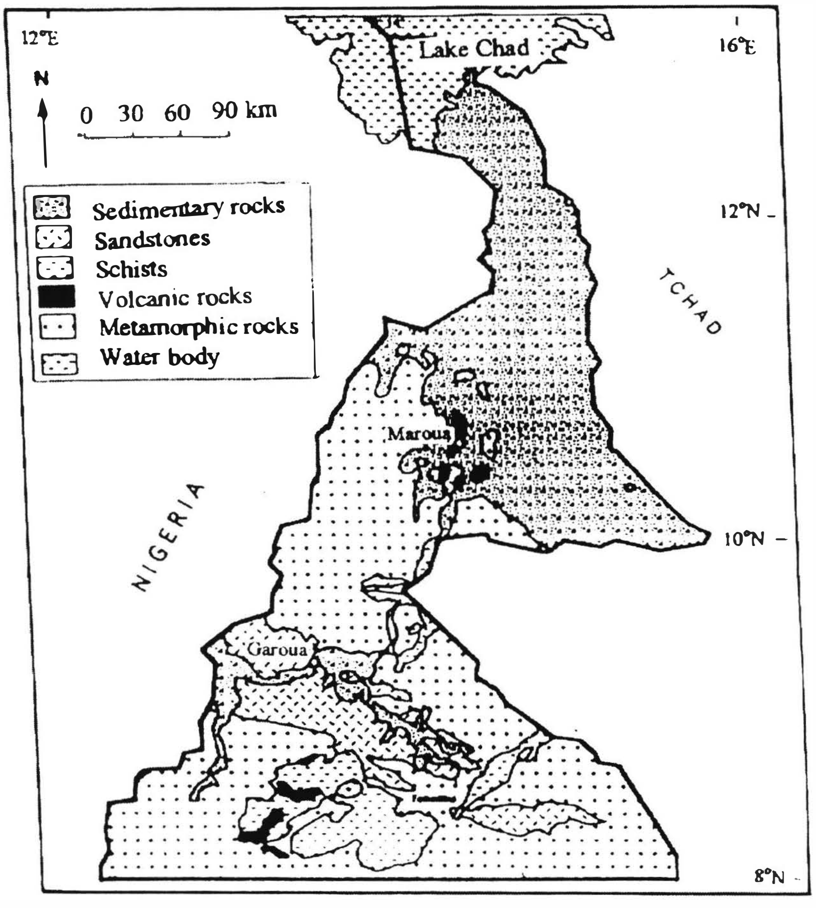


Figure 2.5 Spatial distribution of geologic materials (Braband and Gavaud, 1985)

2.1.4 Geomorphic features

The main geomorphic landscapes are highlands, piedmonts, peneplains/plains and valleys (figure 2.6).

(1) Highlands

The highlands, called "Hosséré" in local dialect, occupy the southeast and west of the area. They consist of two main groups: the Mandara Mounts and the south-Bénoué Hillands.

The Mandara Mounts are composed of hillands (e.g. Matakam Hillands, with the highest summit at 2049 m) and plateaus. Three sets of plateaus are found: (1) low plateaus with an altitude varying between 650 and 750 m; (2) medium plateaus located between the Louti river basin and the Bourha area, with altitude varying between 800 and 1000m; and (3) high plateaus with an altitude higher than 1000 m (e.g. Kapsiki plateau). The south-Bénoué

Hillands have an altitude varying between 1000 and 2000 m, with Poli Mountain as the highest summit (2049 m).

The lithology is composed of plutonic (granites), volcanic (basalt), metamorphic (migmatites) or sedimentary (sandstone) rocks. Many dry rivers (Mayo) originate in these highlands.

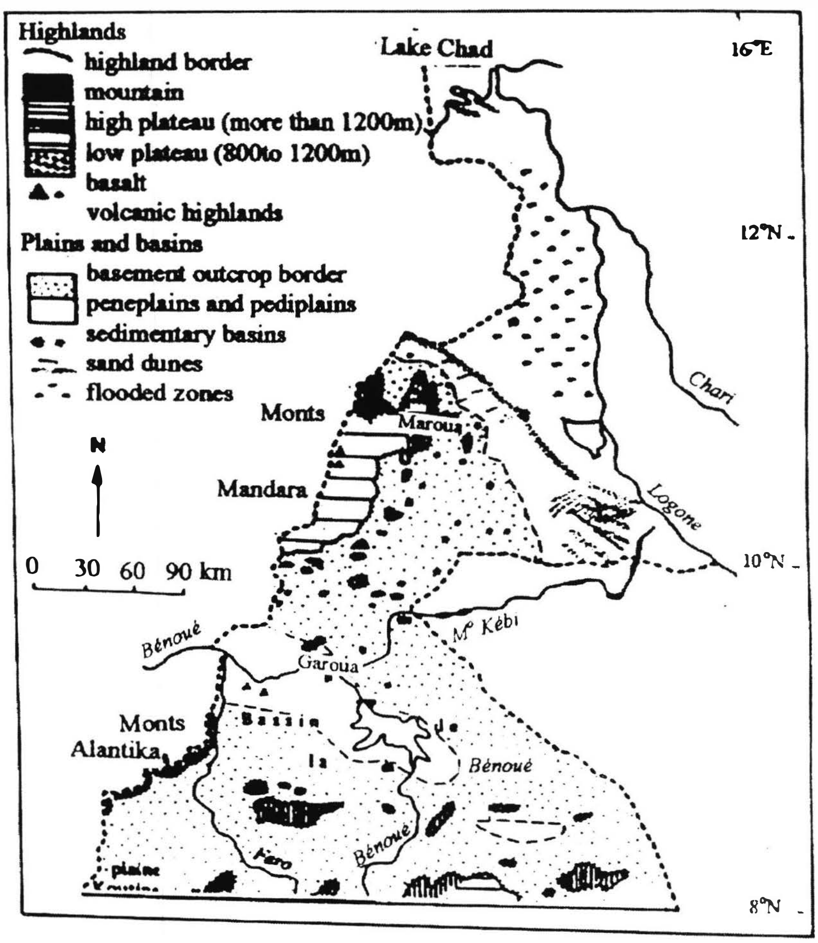


Figure 2.6 Spatial distribution of geomorphic units (Roupsard, 1987)

(2) Piedmonts

Piedmonts are lying at the foot of the highlands. The main relief types are glacis and hills. Their altitude varies between 450 and 650 m.

(3) Peneplains and plains

Peneplains and plains are extensive landscape types in North Cameroon. According to their altitude, they can be divided into three main groups: (1) low plains with altitude of 290 to 320 m and flat topography, corresponding to the Lake Chad depression; (2) medium plains with 320 to 420 m elevation and gentle to rolling topography in the Maroua and Kaélé areas; and (3) high plains and peneplains with altitude higher than 420 m, undulating topography and a relatively dense hydrographic network.

The flat to undulating topography of the plains and peneplains is sometimes interrupted by isolated inselbergs. Peneplains present a varied lithology. Plains are mainly composed of alluvial deposits; some of them, such as the Lake Chad plain, are flooded for some time of the year and are called "Yaéré" in the local dialect.

(4) Valleys

The most important valley in the semiarid area of Cameroon is the Bénoué valley. Three topographic levels compose the Bénoué basin, including: (1) a lower level, with an altitude of 160 to 300 m, extents from the west to the foot of the Tchollire Hillands; the topography is gentle and the alluvial materials are of varied textures; (2) a medium level, in the center of the basin, with an altitude of 300 to 600 m, is built up of erosional glacis and low hills, and presents an undulating topography; (3) an upper level, located in the southeast of the area, is higher than 600 m above the sea level; the topography is hilly and dissected by many tributaries. Other valleys belong to the Logone and Chari rivers in the northeast of the zone.

2.1.5 Soils

Segalen and Vallerie (1962), Humbel and Barbery (1974), and Brabant and Gavaud (1985) showed that the main soils found in North Cameroon are Alfisols, Vertisols, Inceptisols, Entisols and Planosols. Entisols are encountered in areas of steep slopes and in floodplains.

Alfisols occupy flat summits of plateaus or gentle slopes of peneplains. Vertisols are clayey soils in plains and depressions. Inceptisols and Planosols occur on peneplains and plains. The following gives a short description of the five most common soil types in North Cameroon.

(1) Alfisols

Alfisols are mostly red (2.5YR 5/8, dry) or yellow (10YR 7/6, dry) coloured soils and show translocation of clay from the surface horizons to subsoil horizons (argillic horizon). Surface horizons are dark brown (10YR 3/3, dry) to yellowish brown (10YR 5/4, dry), 5 to 28 cm thick, with massive primary structure breaking into subangular blocky to granular secondary structure. The subsurface layers are brown (7.5YR 5/4, dry) or brownish yellow (10YR 6/6, dry), subangular blocky or massive. Subsoil horizons are yellowish brown (10YR 5/8, dry) or red (2.5YR 5/8, dry), with well-formed brown (7.5YR 5/4, dry) clay coatings (clay skins).

The texture varies from loamy sand to sandy clay loam in the surface horizons and from sandy loam to sandy clay in the subsoil horizons. In most cases, the soil profiles show brown or red mottles and have nodules of iron and manganese. Coarse fragments usually occur at various percentages at the surface and in the soil profiles. Organic matter contents vary from 0.7 to 1.4% in the topsoil layers and decrease rapidly with soil depth. Values of pH (1:2.5 soil/water) range from 5.3 to 7.3 in the surface horizons and from 4.9 to 8.7 in the subsoil layers. Surface horizons absorb water more readily than subsoil layers (Segalen, 1962; Humbel, 1967; Brabant and Gavaud, 1985; Van Ranst et al., 1989; Seiny, 1990; and Van Ranst et al., 1990).

(2) Vertisols

Vertisols are formed in fine textured materials. In most years, they have during the dry season open cracks at a depth of 50 cm, that are at least 1cm wide and extend upward to the surface or the base of the plow layer or surface crust. The dominant clay mineral is montmorillonite. The surface layers are dark gray (5Y 4/1, dry) or brownish gray (2.5Y 6/2, dry), 2 to 10 cm thick, with prismatic, subangular blocky or platy structure. The subsoil horizons begin at 3 to 50 cm depth and present shiny surfaces (slickensides). They are dark gray (5Y 4/1, dry) or grayish brown (2.5Y 5/2, dry), with structure varying from prismatic to massive. Cracks were 0.5 to 3 cm wide and 30 to 110 cm deep at the time of the survey (December 1996 to March 1997).

Texture is sandy clay loam in the topsoil layers and sandy clay loam or clay in the subsurface and subsoil horizons. Organic matter contents oscillate between 0.4 and 1.4% in the topsoil and decrease with soil depth. Exchangeable basic cations and pH (1:2.5 soil/water) values increase with soil depth (Segalen, 1962; Humbel, 1967; Brabant and Gavaud, 1985; Van Ranst et al., 1989; Seiny, 1990; and Van Ranst et al., 1990).

(3) Inceptisols

Inceptisols show incipient horizon development. Surface layers are brown (10YR 5/3, dry), 4 to 15 cm thick, with massive primary structure breaking into subangular or granular secondary structure. Subsoil horizons begin at a depth of 10 to 15 cm. They are brown (10YR 5/3, dry) or olive (5Y 5/3, dry), with massive, subangular blocky or prismatic structure.

Texture varies from loamy sand to sandy clay loam in the surface horizons and from loamy sand to clay in the subsoil horizons. Coarse fragments are common in the entire profiles and vary from 4 to 47%. Organic matter contents range from 0.6 to 1.7% in the topsoil layers and decrease with soil depth. Values of pH (1:2.5 soil/water) increase with soil depth. They vary between 7.1 and 8.0, 6.4 and 9.5, 6.8 and 9.6, in the surface horizons, subsurface horizons and subsoil horizons, respectively (Segalen, 1962; Humbel, 1967; Brabant and Gavaud, 1985; Van Ranst et al., 1989; Seiny, 1990; and Van Ranst et al., 1990).

(4) Entisols

In Entisols, diagnostic horizons are virtually absent. On the steep slopes, Entisols are dark brown (10YR 3/3, dry), 6 to 15 cm thick, with massive primary structure breaking into granular secondary stucture. The bedrock begins at a depth of 7 to 16 cm.

Along the valleys, Entisols have yellowish brown (10YR 5/6, dry) or grayish brown (10YR 5/2, dry) subsoil layers, with reddish brown (2.5YR 4/4, dry) mottles and massive, granular or platy structure. The solum is generally more than 50 cm thick and absorbs water readily throughout the profiles. Coarse particles usually occur below 20 to 30 cm depth. Surface horizons are loamy sand or sandy loam. The texture of the subsoil layers varies from sand to sandy clay loam. Organic matter contents, exchangeable basic cations and pH (1:2.5 soil/water) fluctuate with soil depth, which can be attributed to the variation in the nature of the alluvial deposits (Segalen, 1962; Humbel, 1967; Brabant and Gavaud, 1985; Van Ranst et al., 1989; Seiny, 1990; and Van Ranst et al., 1990).

(5) Planosols

Planosols have one or more upper horizons with a relatively low clay content, which abruptly overlay a deeper and less permeable horizon with considerably high clay content. Surface horizons are brown (10YR 5/3, dry), reddish brown (5YR 5/3, dry) or yellowish brown (10YR 5/4, dry), 3 to 15 cm thick, with massive primary structure, breaking into granular secondary structure, or columnar. A white (10YR 8/1, dry), single-grained eluvial horizon occurs between 12 and 54 cm depth. Subsoil horizons are yellowish brown (10YR 5/4, dry) or brownish gray (2.5Y 6/2, dry), with massive or columnar structure.

Texture varies from sandy loam in the surface horizons to clay loam in the subsoil horizons. Coarse particles occur in the entire profile and vary between 4 and 26%. Organic matter contents oscillate between 0.44 and 1.72% in the topsoil layers and decrease rapidly with soil depth. Exchangeable basic cations and pH (1:2.5 soil/water) increase with soil depth (Segalen, 1962; Humbel, 1967; Brabant and Gavaud, 1985; Van Ranst et al., 1989; Seiny, 1990; and Van Ranst et al., 1990).

2.1.6 Hydrology

The drainage system of the semiarid zone of Cameroon belongs to two main watersheds: the Lake Chad watershed in the northern part and the Bénoué watershed in the southwestern part. In the north, the drainage system consists of the Logone and Chari rivers, which flow from southeast to northwest. The Bénoué watershed is the most important one and covers about 92000 km^2. The Bénoué river flows from east to west. Its tributaries are Mayo Kébi and Faro rivers (figure 2.7). The Bénoué river discharges an average of 400 m^3 per second in the dry season and 2000 m^3 per second during the rainy season (GTZ, 1980).

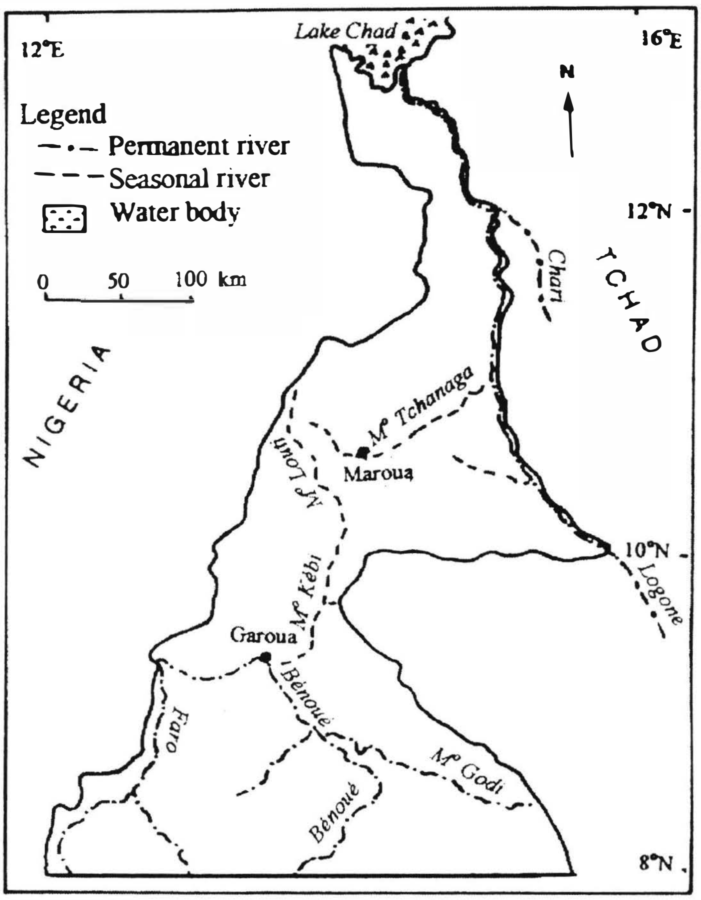


Figure 2.7 Spatial distribution of the main rivers (Letouzey, 1968)

Other types of surface water are seasonal rivers that flow only during the rainy season. Water keeps flowing under the river beds for some weeks or months after the rainy season. Groundwater level varies according to seasons, the distance from a river and the local geomorphology.

2.1.7 Vegetation

There is a close relationship between vegetation, soil type and agroclimatic zone. Letouzey (1968) distinguished four main groups of vegetation, including (1) tree savannahs, savannah woodlands and dry woodlands, (2) highland vegetation, (3) tree and shrub steppes, and (4) vegetation of periodically flooded areas (figure 2.8).

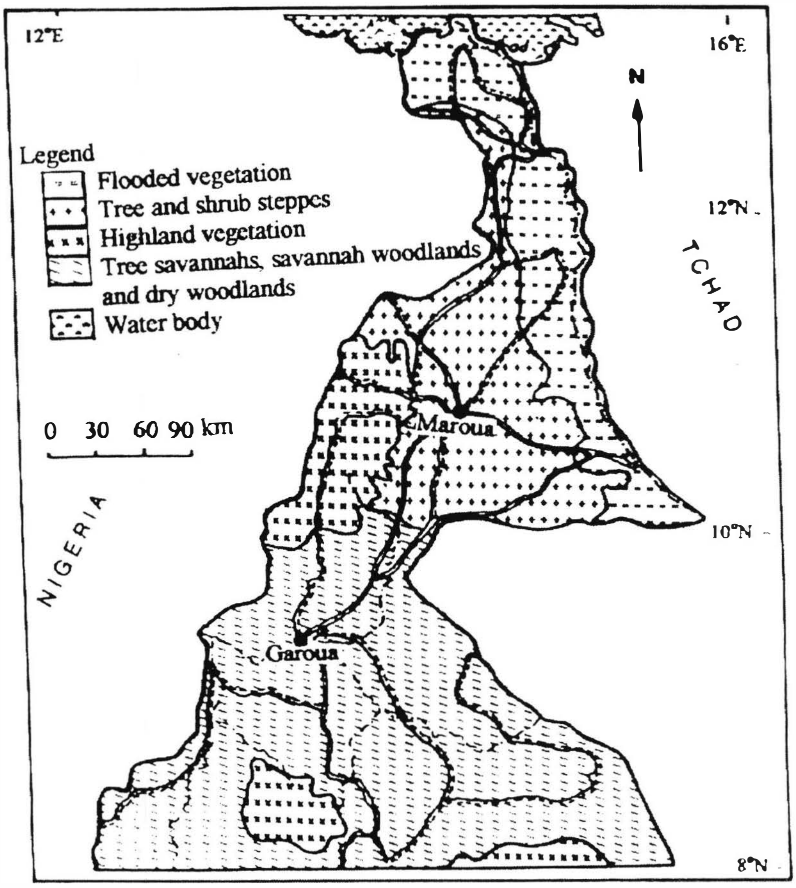


Figure 2.8 Spatial distribution of vegetation types (Letouzey, 1968)

(1) Tree savannahs, savannah woodlands and dry woodlands

Tree savannas, savanna woodlands and dry woodlands belong to the soudanian agroclimatic zone. They are the most important in terms of extent and species richness. The main species are: *Monotes kerstingii, Burkea africana, Anogeissus schimperi.* The grass layer is composed of *Digitaria uniglumis, Loudetia arundinacea* and *Hyperrhenia sp.* Secondary species encountered are: *Acacia caffra var. Campylacantha, Afzlia africana, Daniellia oliveri, Tamarindus indica, Adansonia ditata, Boswellia odorata* and *Faidherbia albida. Borassus aethiopumm, Bombax costatum* or *Tamarindus indica* are linked to the presence of humans. This vegetation occurs mainly on Alfisols in plains and peneplains.

(2) Highland vegetation

Highland vegetation is found north of the latitude 10° N and at altitudes between 600 and 1200 m. Certain characteristic species, such as *Isoberlinia* and *Adansonia digitata,* are short-sized here and flower in that state. Other species are *Boswellia dazielii, Combretum sp., Diospyros mespiliformis* and *Woodfordia uniflora.* That group of vegetation grows on shallow highland soils.

(3) Tree and shrub steppes

Tree and shrub steppes grow in the sahelian agroclimatic zone, on Alfisols and Vertisols. The main species are: *Faidherbia albida, Acacia senegal, Calotropis procera, Combretum micranthum, Guiera senegalensis, Bosci angustifollia, Acacia seyal*, and *Acacia ataxacantha.*

(4) Vegetation of periodically flooded areas

Periodically flooded areas occur along the Logone river. This is a vast water-logged area, called "Yaéré" in the local dialect and covered by approximately one meter water during the rainy season and for some months after the rainy season. The dominant vegetation species encountered are: *Hyparrhenia, Vetiveria nigritiana, Caratophyllum sp., Cyperus papyrus, Echinochloa pyramidalis, Phragmites communis* and *Vossia cuspidata.*

The vegetation cover has been degraded by human activities (agriculture, fire wood, building) and by soil erosion. This has changed the natural equilibrium between the different agroclimatic zones and their respective vegetation. Because of increasing aridity, vegetation species from dry areas, characterized by low biomass, are replacing the relatively high biomass species.

2.1.8 Land use

Agriculture and animal husbandry are the main activities in North Cameroon. The main crops are sorghum, millet, maize, beans, groundnut and varied vegetables. The only cash crop is cotton. Irrigated agriculture (market gardens) is practiced along the rivers. Livestock is composed of cattle, goats, sheep and donkeys.

2.2 THE GAWAR STUDY AREA

The choice of the Gawar area is based on the following considerations: (1) it lies approximately in the centre of the semiarid zone of Cameroon; (2) it contains varied geomorphic units and soil types; (3) it includes traditional villages as well as pioneer settlement areas; (4) it is relatively densely populated; and (5) it is a pilot area receiving special governmental and non-governmental attention. The study area offers a variety of geomorphic units, soils, cropping systems and management practices.

The Gawar area is situated between the latitudes 10° 18' to 10° 41' N and the longitudes 13° 45' to 14° 00' E (figure 2.9). The area covers about 80,000 hectares. The agroclimatic zone is soudano-sahelian, modified by orographic effect. The annual rainfall varies between 800 and 1000 mm. The average annual temperature is 28° C.

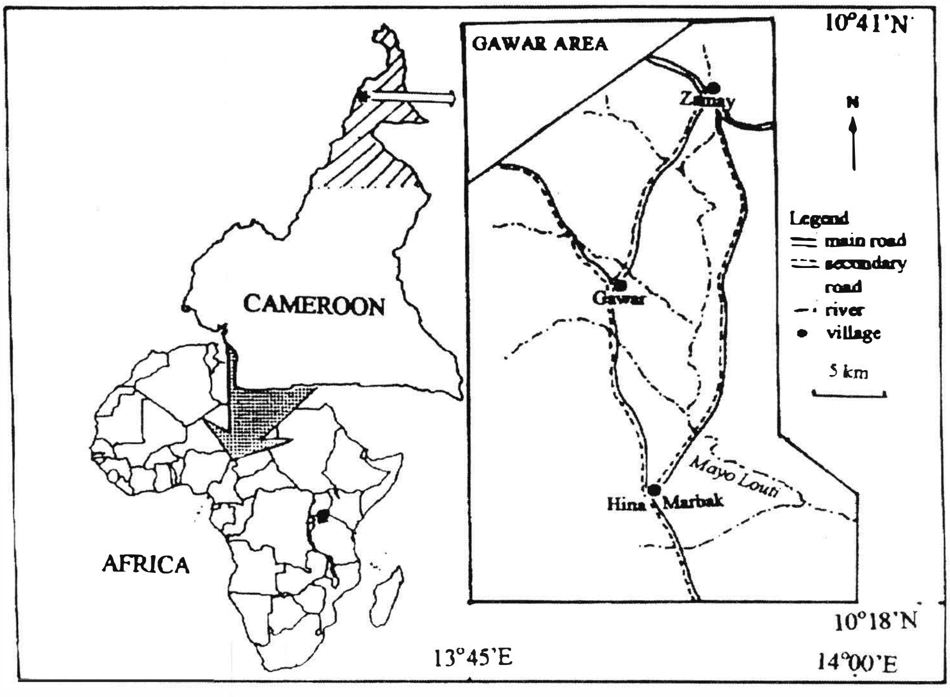


Figure 2.9 Location of the Gawar study area

2.2.1 Geomorphic units and soils

Despite the relative homogeneity of the climatic conditions in the study area, there is a high variability in soil types, correlated to the variability of the geologic (figure 2.10) and geomorphic conditions (figure 2.11). The typical geomorphic profile consists of mountain, plateau, hilland, piedmont, plain/peneplain and valley. The following section describes the main landscapes in the Gawar study area.

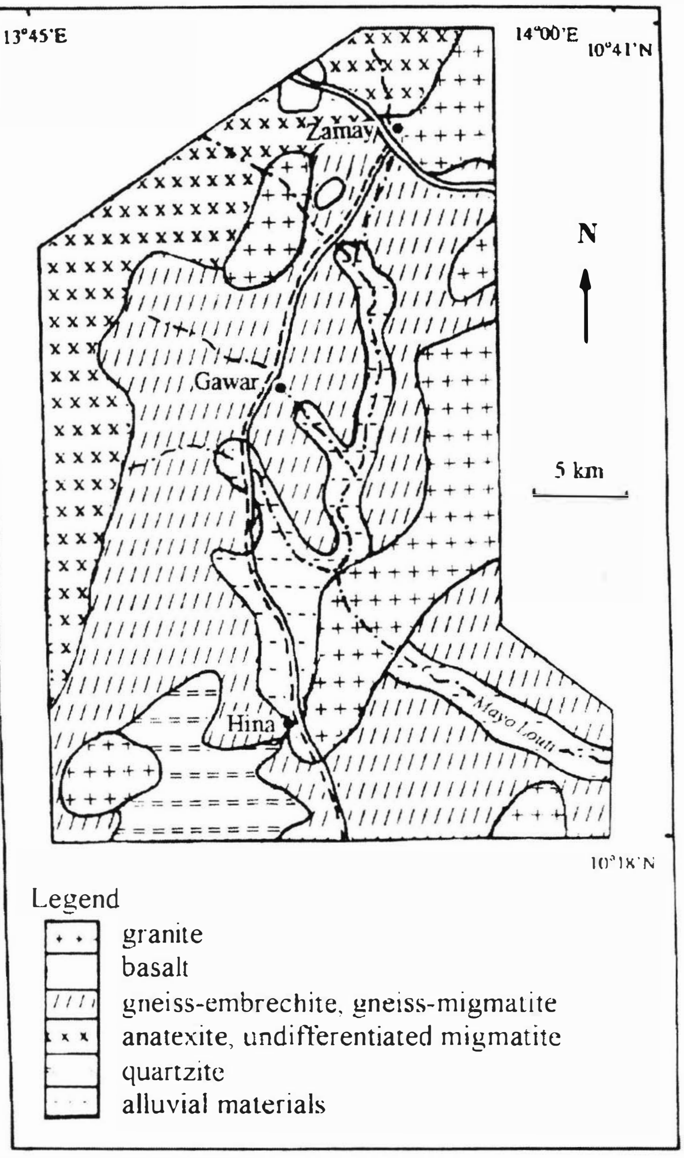


Figure 2.10 Spatial distribution of geologic materials (adapted from Segalen and Vallerie, 1962; Sieffermann, 1963)

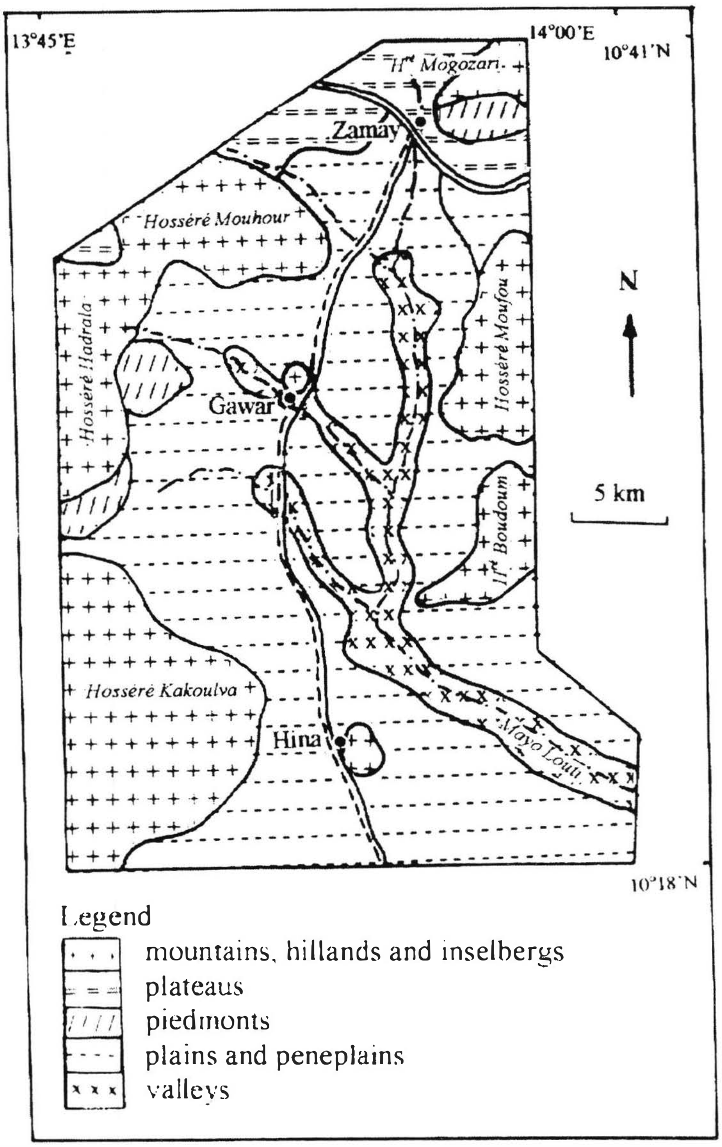


Figure 2.11 Spatial distribution of geomorphic units (adapted from Segalen and Vallerie, 1962; Sieffermann, 1963)

(1) The mountains

A mountain is an elevated, rugged land portion characterized by an important relative height and steep slopes in relation to lower-lying surrounding landscape units, and by an important internal dissection, generating high relief energy (Zinck, 1988). The mountains occur at elevations ranging between 700 and 1060 m and occupy an area stretching roughly between the latitudes 10°18' to 10°40' N and the longitudes 13°45' to 13°52' E. Four mountain ranges cover about 25% of the total area: (1) Hosséré Moufou and Hosséré Boudoum in the east, (2) Hosséré Hadrala in the west, (3) Hosséré Mouhour and Hosséré Mogozari in the north, and (4) Hosséré Kakoulva in the southwest. The mountain ranges are separated either by plains, peneplains, plateaus or narrow valleys. Notable landforms include rocky summits, steep and bouldery backslopes and rubbly footslopes.

The geologic materials include granites, anatexites, migmatites, basalts, and quartzites. In these rugged and very steep landscapes, soil development is disturbed by erosion of surficial materials along the slopes and colluviation at the footslopes. Entisols prevail, characterized by a thin A horizon lying on the bedrock and a high accumulation of boulders at the soil surface. The soils are dry over most of the year.

Because good land is scarce, the mountains support most of the human activities. However, the environmental sensitivity of the mountains and their inherently low productivity impose constraints on crop and animal productions, thus demanding careful management. Some areas where soil conservation measures (stone wall terraces) are implemented, allow for intensive rainfed cropping.

(2) The hillands

A hilland is a rugged land portion characterized by the repetition of high hills, generally elongated, with uneven summit heights, separated by a moderately dense hydrographic network (Zinck, 1988). The hillands in the Gawar area consist of miscellaneous collections of hills showing steep slopes, with elevation ranging from 700 to 965 m. They occupy the eastern part of the study area and cover about 15% of the total area. The hills are characterized by rocky summits, rocky and bouldery backslopes and some colluvium at the footslopes. The geologic material is mainly granite.

Notable features of the soils are thin A horizons lying on the bedrock. Entisols are found on the backslopes, while some Inceptisols are encountered at the footslopes. The soils are dry over most of the year. Due to the narrowness of the ridges and the steepness of the slopes, possibilities for crop and animal productions are small. Agricultural activities are sporadic.

(3) The plateaus

A plateau is a large, flat, unconfined, relatively elevated land portion which is commonly limited on at least one side by an abrupt descent (escarpment) to lower land (Zinck, 1988). The plateaus occupy mainly the northern part of the study area and cover about 15% of the total area. Their altitude varies between 700 and 900 m. The degree of dissection of the plateaus varies from place to place. In the eastern part of the area there is a large undissected tract with flat to gentle topography (mesa) at elevations of 850 to 900 m. However, the surface is interrupted by some entrenched gullies. Where topography is rolling, the plateau is an erosional surface displaying various degrees of dissection by temporary streams with variable depth of entrenchment, which gives rise to low ridges (half-oranges) of various sizes.

The geologic material includes granites, anatexites, migmatites, gneiss and embrechites. The soils are homogeneous over large areas, except on rolling surfaces where changes occur at short distances due to the influence of the topography or of the parent material. Alfisols are encountered on areas of flat topography. Entisols are found on the escarpments, whereas Alfisols, Inceptisols and Entisols are associated on rolling topography. Alfisols have dark brown (10YR 2/2 dry) to yellowish brown (10YR 5/4 dry), loamy sand to sandy loam, massive to subangular blocky topsoil layers, on top of redder (2.5YR 4/8 to 2.5YR 5/8 dry), finer textured, moderately thick, subangular blocky Bt horizons, which tend to restrict water percolation. The plateaus offer a wide range of land use possibilities, but their limited accessibility reduces the expansion of agriculture and livestock.

(4) The piedmonts

A piedmont is a sloping land portion lying at the foot of a mountain, hilland or plateau (Zinck, 1988). The piedmonts in the Gawar study area occur at an elevation varying from 500 to 700 m and consist of glacis and hills. They are lying between the southern slopes of the "Hosséré Mogozari" mountain and the escarpment of the Zamay plateau in the northeast part of the study area, and between the eastern slope of the "Hosséré Hadrala' and the Gawar plain in the western part. The geologic material includes granites and migmatites.

Most common soil types belong to the Alfisols and Inceptisols. The steep slopes of the piedmont hamper the expansion of human activities.

(5) The peneplains

A peneplain is a gently undulating land portion, characterized by a pervasive repetition of low hills, rounded or elongated, with summits of similar heights, separated by a dense, reticular hydrographic network (Zinck, 1988). The peneplains occupy the southwest part of the study area at an elevation ranging from 600 to 650 m. The topography is undulating to rolling, which results in rounded ridges (half-oranges) of contrasting structures and geological materials. The geology includes granites, anatexites, migmatites, embrechites and quartzites. The main soils are Alfisols, Inceptisols and Entisols in associations. Rainfed agriculture and extensive livestock are actively practiced here.

(6) The plains

A plain is a large, flat, unconfined, low-lying land portion with low relief energy (1 to 10 m of altitude difference) and gentle slopes (Zinck, 1988). The plains occupy the center of the study area and consist of extensive zones of low relief lying below highlands, at elevations ranging from 510 to 600 m. They cover about 35% of the total area. The surface is entrenched by the Mayo Louti river and its tributaries (Mayo Gawar, Mayo Ladé and Mayo Moudal), which flow from northwest to southeast.

The main relief features are terraces built up probably by successive entrenchments by the Mayo Louti river. Locally, networks of deep rills and gullies cross the terraces, indicating severe erosion. In many places, there is a thin layer of eolean deposits (silt and sand) at the soil surface, which is an evidence of wind erosion in the study area.

Soils are varied as a result of variations in parent material and local topography. Areas with impeded external drainage have clayey soils, while areas of rapid external drainage show exposed bedrocks. The soil solum is structurally and chemically controlled by the parent material and the leaching process. Consequently, texture varies from fine to coarse, colour varies from dark brown (10YR 3/3, dry) to reddish brown (2.5Y 4/4, dry) or yellowish brown (10 YR 5/6, dry), structure ranges from massive to columnar and subangular blocky, and pH (1:2.5 soil/water) is slightly alkaline to slightly acid, in the B horizons. Major soils include Alfisols, Vertisols, Inceptisols and Planosols.

Because of good accessibility and a wide range of soil types, the plain landscape supports much human activities. Less eroded soils provide areas for intensive cropping and extensive grazing; more eroded soils are devoted to extensive grazing and firewood harvesting.

(7) The valleys

A valley is an elongated, flat stretch of land intercalated between two bordering, higher landscapes (mountain, plateau or hilland) (Zinck, 1988). The valleys in the Gawar study area consist of incised areas by the Mayo Louti river and its tributaries. Their elevations vary between 500 and 580 m. They are the lowest landscape units in the region and cover about 5% of the total area. Narrow and elongated areas of alluvial sediments border the streams. The floodplain enlarges where the main river (Mayo Louti) crosses the Gawar plain. Because of frequent flooding, soil development is limited by sediment accumulation, causing the formation of Entisols. The profile of these soils consists of distinct layers due to the variations in sediments rather than to soil horizon development, with some mottling in the lower horizons. On valley terraces built up of older deposits, soil development is sufficient to allow the formation of Inceptisols.

In the large low-lying floodplains, soil texture is silty or sandy. In the narrow floodplains on steep and high intermountain areas, the soil texture is often gravelly. In general, the texture of the soils in the floodplains depends on the velocity of the river and the type of bedrock in the upper drainage basin. The valley bottoms are used for intensive agriculture because they are flat, and provide water for irrigated crops over most of the year.

Generally speaking, the geomorphic profile of the area consists of two main zones where removal of surface materials and deposition of soil materials take place, respectively. In the removal zone, erosion processes are dominant. The soil thickness decreases and there is an active balance of denudation. This zone includes highlands, piedmonts and peneplains. In the depositional zone, sedimentation processes prevail. Soil depth increases by weathering or by addition from upslope colluvium or from upstream alluvium. This situation is termed passive balance. The main landscapes concerned are plains and valleys. However, denudation processes start under human activities.

2.2.2 Settlement types

There are two types of settlement: (1) the traditional settlement which consists of autochtonous groups of people; and (2) the colonization settlement consisting of groups of settlers who came from overpopulated highlands (Mandara Mounts). The combination of local population growth and immigration has resulted in a relatively high population density in the area, increasing from 150 inhabitants/km^2 in 1976 to more than 200 inhabitants/km^2 in 1987 (PNUD-UNSO, 1993). This makes the area to be one of the most crowded in the semiarid zone of Cameroon.

2.2.3 Land use

Agriculture and animal husbandry are the dominant activities. The main crops are sorghum, millet, maize, groundnut, beans and vegetables. Cotton is the main cash crop in the area. Livestock is composed of cattle, goats, sheep and donkeys. Intensified land use under existing farming systems has resulted in soil erosion, desertification and expansion of agriculture on marginal lands called "Hardé" (meaning sterile soils in the local language), formerly used for grazing and fuel wood harvesting (Seignobos, 1991). High human and animal population densities cause land use conflicts between different land users.

2.2.4 Pilot area

In the Gawar area, many governmental and non-governmental organizations were/are working in different field activities, as for instance:

- Soil surveys at different scales have been done in many parts of the area (Segalen and Vallerie, 1962; Sieffermann, 1963; Pontanier and Kotto-Samé, 1982 ; Brabant and Gavaud, 1985);
- Research on farm economics and environmental aspects have been conducted in the area (Ngono, 1992; CEDC, 1995; SNV, 1995;);

- Projects and programs with practical relevance for environmental conservation were implemented (Nankia, 1996; CARE-Projet S.O.S Louti Nord, 1995; SNV, 1995);
- Actions in economic, social, educational and health domains for welfare development in the Gawar area are conducted by non-governmental organizations in collaboration with governmental structures (CARE, 1995; SNV, 1995);
- Aerial photographs at the scale of 1/30,000 dated June 1993 were available (ONADEF-Mokolo, 1993) and suitable for erosion studies in the area.

Considering physical and human factors, the Gawar area seems to fulfill the requirements for rural development. Still, farmers face problems of soil degradation by erosion. As far as rural development is concerned, more attention should be paid to environmental issues, since the farmer is particularly vulnerable to the deterioration of the soil resource, for the quality of his life depends on the preservation and productive capacity of his land (Collins, 1981). It is thus relevant to monitor, with respect to soil erosion, the land use planning scheme designed for the Gawar area.

CHAPTER 3

CONCEPTUAL FRAME

Many studies have been conducted on accelerated soil erosion, providing a huge amount of publications. This chapter presents the conceptual frame, including conventional concepts, definitions of terms, and opinions related to soil erosion and conservation. It reviews the causes of accelerated soil erosion by water, its principles, the prediction models and the control measures.

3.1 CAUSES OF SOIL EROSION

Geological erosion, usually referred to as natural erosion acting over long geological periods, occurs when the soil is in its natural environment. This type of erosion is the main factor responsible for the formation of most of the present topography.

Soil erosion by water is the detachment and transport of soil material caused by the action of the water. It results from a perturbation in the land-vegetation-climate equilibrium, primarily by human activities. This type is called accelerated soil erosion. Socio-economic and political factors play a great role in man-induced erosion. Some of the factors described by Lal (1990), Hudson and Rodney (1993), Hudson (1996) and Nill et al. (1996), are given as follows:

- Poverty of the farmers: the lack of capital may hamper the use of erosion control measures and enhances damaging practices (deforestation, overgrazing). Mostafa and Osama (1992) reported that deforestation and overgrazing contribute to soil erosion in the proportions of 29% and 35%, respectively.
- Unbalanced population density: overpopulation resulting from high growth and immigration may cause overuse of land. But, underpopulation due to migration may also have detrimental effects. Blaikie (1985) and Vogel (1988) argued that traditional terraced agro-systems were destroyed in Yemen after the migration of the rural

population, or the soil conservation work undertaken in the Gurka area in India was damaged after the recruitment of the Gurka into the British army.

- Institutional frame: the lack of defined conservation policy and laws to regulate the use of the land may prevent farmers from applying soil conservation practices. Inadequate economic incentives to farmers and the failure to adapt or adopt new agricultural technologies may also explain soil erosion.
- Land tenure: the traditional inheritance system sometimes favours a continuous fragmentation of the farms, which leads to the overuse of land. The lack of land tenure creates little incentive for the occupant to introduce long-term improvements to maintain the optimum level of soil fertility

3.2 SOIL EROSION PRINCIPLES

3.2.1 Processes that retard erosion

(1) Interception

Interception storage can be defined as that portion of the precipitation that adheres on vegetation leaves and grass blades, or on aboveground objects, and later returns to the atmosphere through evaporation. In semiarid areas and on arable lands, there is no interception storage because of the lack of vegetation at the beginning of the rainy season.

(2) Soil surface roughness and aggregate stability

When rainfall intensity exceeds the infiltration capacity of the soil, rainfall excess begins to fill numerous small depressions. From these the only escape is evaporation or infiltration. These small depressions provide depression storage. Micro-relief consists of depressions of various sizes, which are both superimposed and interconnected. After the beginning of the rainfall excess, the smallest depressions are filled first and overland flow begins. Some of the water flow follows unobstructed paths and fills larger depressions until all of the depression storage within the catchment is filled (Linsley et al., 1949). The portion of water, other than the depression storage, which remains in temporary storage on the soil surface as it moves downslope by overland flow, is known as surface detention (Horton, 1933; Linsley et al., 1949; Ven Te Chow, 1959). The nature of the depressions as well as their size depend on the soil characteristics and land-use practices.

Soil surface roughness on agricultural lands is usually the micro-relief formed by tillage implements. It is nondirectional and characterized by the presence of aggregates and clods (Helming, 1993). Soil surface roughness and related resistance to flow are important soil characteristics, which affect the rate of water advance, the rate of recession and, indirectly, the infiltration depth. It can serve as a qualitative estimate of soil strength and of the susceptibility to sealing (Levy et al., 1994). Heermann et al. (1969), Hugging and Burney (1982), Römkens and Wang (1986), Nearing (1990), Govers (1991), and Mwendera and Feyen (1992) demonstrated that surface micro-topography, associated hydraulic flow resistance and changes thereof due to rainfall are important factors in soil erosion and runoff processes.

Several methods to measure soil surface roughness have been developed. Allmares et al. (1966) calculated an index from the standard deviation of smoothed elevation points. Lehrsch et al. (1988) used geostatistical procedures to investigate the spatial distribution of elevation points. Depression storage is assumed to be an important microrelief parameter, that allows for physically-based interpretation of microrelief effects on infiltration and runoff (Helming et al., 1993). Although the importance of knowledge on surface roughness for describing runoff and erosion processes is widely recognized, few studies involving quantitative description of surface roughness have been conducted (Römkens, 1988).

In most hydrologic models, the values of Manning's resistance coefficient for natural surfaces are considered constant. However, tillage-induced micro-topography on agricultural lands is continuously changing due to erosion, deposition and consolidation processes. Therefore, a method of updating the resistance coefficient in relation to the changing surface conditions is likely to improve the assessment of overland flow and soil erosion from agricultural lands. It can then be potentially incorporated into simulation models of soil erosion (Mwendera and Feyen, 1992). Several researchers applied simulated rainfalls under laboratory conditions in search for a roughness parameter, which could be related to a flow resistance index (Kruse et al., 1965; Heermann, 1969; Das, 1970; Kundu, 1972). Random roughness is computed simply as the standard deviation of the height measurements after oriented roughness has been removed (Kuipers, 1957; 1989; Mwendera and Feyen, 1992).

Several soil characteristics have been studied for their influence on soil surface roughness. Stability of soil surface aggregates might affect soil surface roughness changes. Stability of aggregates is probably the most important soil property governing soil erodibility. Physical, chemical and mineralogical soil properties, which influence aggregate stability, should ultimately influence the erodibility of the soil. Aggregate stability is largely dependent on organic matter, clay and oxide contents. Aluminum and iron oxides promote aggregation. Stability of clayey soils depends on the physico-chemical properties of the clay. Increased hydrogen and aluminum ions were related to increased aggregation caused by their flocculating and binding capacity (Kemper and Koch, 1966; Bryan, 1968; El-Swaify and Emerson, 1975; Miguel and Darrel, 1994).

(3) Infiltration

Infiltration is the downward entry of water into the soil through the soil surface. As water infiltrates into the soil, a part of this replenishes the soil moisture storage (or retention storage) which sustains the growth of vegetation, and the other part goes deeper and recharges the aquifers and ultimately becomes the source of groundwater for wells, springs and streams during the dry periods (Glenn, 1981; Warren et al., 1989). Infiltration determines the availability of precipitation input for generating overland flows. Water at the leading edge of the wetting pattern advances into the soil ahead of the front under the influence of matric potential gradients as well as gravity. The infiltration rate is defined by the flux of water across a land surface into the soil. The maximum rate at which water is absorbed by the soil, which is equal to the infiltration rate of ponded water, is termed infiltration capacity.

During the early stage of infiltration and when the soil is dry, the wetting front is near the surface, the matric potential gradient predominates over the gravitational force, which gives rise to high infiltration capacity. When the matric forces are dominant, the wetting front tends to be symmetrical and moves as much laterally as vertically. If gravity is more important, then the front is elongated and tends to an ellipsoidal shape (Tsuyoshi et al., 1993).

The matric potential gradients decrease with time due to advancement of the wetting front into the deep soil zone, and the infiltration capacity decreases. The infiltration capacity approaches asymptotically the final infiltration rate. When new water penetrates wet soils, the existing water is expelled from its position and pushed out by the infiltrated water. Water in the vicinity of the wetting front in the wet soil is composed of initially contained water pushed out by the newly penetrated water. Water does not move smoothly into the soil, but sometimes accumulates behind the apparently resting wetting front; then when the equilibrium of the wetting front is destroyed, it will suddenly spring into adjacent pores (Morin et al., 1989; Tsuyoshi et al., 1993).

Many mathematical formulations of infiltration have been developed. Green and Ampt (1911) developed the first equation of infiltration based on a physical model. Kostinakov (1932) developed empirical equations where he tried to obtain fitting parameters to approximate the infiltration curve. Horton (1933) developed an equation that describes the general features of infiltration in different soils. The reliability of his equation lies in the physical reality of the effective pressure head at the assumed wetting front. But this equation was deduced from an oversimplified moisture profile model. Philip (1957) developed a one-dimensional flow equation for horizontal flow, vertical-down flow and vertical-up flow. Although the applicability of Philip's method is restricted to particular initial and boundary conditions and to uniform soils, it provides useful analytical solutions for infiltration.

The reduction in infiltration rate with time during the infiltration process is largely controlled by factors operating at the soil surface such as crust formation. Pore saturation by water or clogging by sediment and swelling clays affect the infiltration process (Romkens, 1990). Vegetation and stone covers, initial water content, water potential gradients, and the soil profile characteristics also control the infiltration rate (Baver et al., 1972; Morin et al., 1989; Römkens, 1990; Cerdà, 1996). Infiltration is a factor that has a great influence on overland flow and, therefore, on soil erosion. Generally, a high infiltration rate curtails the amount of overland flow and reduces soil erosion. Human activities, such as agriculture and pasturing, can negatively affect infiltration rates and accelerate erosion processes (Carlos, 1995).

The infiltration process is very complex because of the great variability of soil characteristics upon which it depends. Many soil properties are known to influence the hydraulic conductivity and infiltration rate: organic matter content, iron oxides, clay mineralogy, texture and exchangeable cations. Morin et al.(1989), Levy and Van Der Watt (1990) reported that increasing potassium in the exchangeable phase resulted in a decrease in both the hydraulic conductivity and the infiltration rate of the soil.

Theoretically, the final infiltration rate of ponded water is at least equal to the saturated hydraulic conductivity, because there must be no matric gradient at the land surface in the final stage of infiltration. However, this is not always the case. Final infiltration rates have been reported to be smaller than the saturated hydraulic conductivities. The reason for this discrepancy is that soil saturation by ponded water proceeds downward from the soil surface, leaving much entrapped air. Evaporation from the soil causes upward flow of water from the bottom to the soil surface, which reduces the entrapped air. The difference between these is attributed to the difference in the volume of entrapped air, which reduces the flow of water into the soil.

A certain number of factors could explain the discrepancies between laboratory and field experiments on infiltration. Field soil profiles are not uniform with depth, nor is the water content distribution at the initiation of infiltration. These tend to reduce the infiltration rate more rapidly than would be predicted from a model that considers the soil was throughout homogeneous. The reduction of infiltration observed in non-homogeneous soils is due to the presence of horizons of lower permeability. The infiltration models assume that the surface is maintained at a fixed potential. Under rainfall, the only time that the surface would be exposed to a fixed potential is when the rainfall rate is so intense that ponding begins immediately. Most of the infiltration models deal with one-dimensional infiltration in which water is assumed to flow vertically into the soil. In the field situation, water enters into the soil and moves laterally as well as vertically (William et al., 1991).

(4) Soil moisture content

Soil moisture content is that portion of infiltrated water that remains binded by soil particles and sustains the growth of vegetation. Soil moisture content limits plant growth either because there is too much (swampy areas) or too little (arid areas) in the soil (Marshall, 1963).

Antecedent soil moisture content, which represents the amount of water content in the soil prior to a rainfall, affects soil cohesion and strength, aggregate stability, runoff and soil erosion (Barnett and Rogers, 1966; Lyles et al., 1974; Kamper et al., 1987; Truman and Bradford, 1990).

3.2.2 Processes that promote erosion

(1) Splash erosion

Splash erosion is a detachment and air-borne movement of small soil particles caused by the impact of raindrops on the soil (Soil Science Society of American Journal, 1987). Considerable quantities of soil are splashed into the air when the soil is bare. Soil aggregates and other soil structural elements, such as clods produced by tillage, resist splash to a degree depending on the aggregates or, in general, the structural stability.

The process of splash erosion involves soil detachment and soil transportation by raindrops that occur by either saltation or creep. The corresponding soil characteristics that describe the ease with which soil particles may be detached and transported are soil detachability and soil transportability.

Surface soil moisture and the availability of loose detachable sediments influence splash erosion (Parson, 1994). Rates of raindrop detachment have been shown to vary within a rainfall event. Ellison (1945), Cruse and Larson (1977), Ghadiri and Payne (1981), Francis and Cruse (1983), Torri et al. (1987) and Bradford et al. (1987) reported that the increasing splash rate prior to ponding is believed to be due to decreasing shear strength and aggregate stability with increasing soil moisture content. The decrease after ponding is attributed to the increasing depth of water, which reduces raindrop impact stress and hence detachment at the soil surface, or by the diminishing availability of loose detachable sediments, or by crust development. Splash erosion is a source of sediments to be transported by sheet flow (Ellison, 1945; Parson et al., 1994).

There is a positive correlation between soil detachability and soil particle size, while there is a negative correlation between transportability and soil particle size. In fact, soil detachability increases as the size of the soil particles increases, and soil transportability increases with a decrease of soil particle size (Glenn, 1981). Consequently, clay is more difficult to detach than sand, but clay is more easily transported.

Factors that affect the direction and distance of soil splash are rainfall characteristics, antecedent moisture status, bulk density, soil shear sthrength, slope angle, wind, surface condition, and aggregate stability (Palmer, 1964; Bubenzer and Jones, 1971; Al-Durrah and Bradford, 1981; Sharma and Gupta, 1989; Moore and Singer, 1990; Slattery and Bryan, 1992).

On sloping land, the splash moves farther downhill than uphill, because the angle of impact causes the splash reaction to be in downhill direction. Surface roughness and impediments to splash tend to counteract the effect of slope and wind (Glenn, 1981). Styczen and Nielsen (1989) presented some splash erosion characteristics as follows:

- the impact of drops can be described as an unelastic collision;
- energy is needed to detach soil (breaking bonds between micro-aggregates);
- most of the energy is spent in the detachment process.

Splash erosion rates decrease as the runoff depth increases. This indicates that the detachment power of raindrops is partially dispersed by the layer of overland flow. On steep slopes, there is a tendency of fast disposal of water, hence a shallow water layer; therefore, rainsplash erosion could be an important form of erosion on steep slopes (Morgan, 1986). Splash dislodges material and interrill flow conveys the material dislodged by splash, although detachment of particles probably also occurs by overland flow in interrill erosion.

(2) Crust and seal formation

Crusting or sealing is the formation of a thin layer (1 to 5 mm) at the surface of the soil by the beating action of the raindrop impact. Crust formation is due to the physical desintegration of soil aggregates and their compaction, and the physico-chemical dispersion and movement of clay particles that lodge and clog the conducting pores. The two mechanisms act simultaneously as the first enhances the latter (Agassi et al., 1981). Ellison (1947) and Moore and Singer (1990) summarized changes in the erosion processes during crusting as a transformation from high detachment-low transport (interrill-dominated) to a low detachment-high transport (rill-dominated) system. Numerous systematic studies have investigated the processes involved in crust formation. Petrographic microscope techniques revealed three types of surface seal:

- Disruptional seals formed on interrill areas due to rapid destruction of surface aggregates by direct raindrop impact, rearrangement of disrupted fragments and textural separates by splash transport, and compaction and flattening of the surface material by continued drop impact. Seals formed by these processes are referred to as "structural", "compacted structural" (Valentin and Bresson, 1992) or "disruptional" (Slattery and Bryan, 1994).
- Sedimentational seals develop under rill and interrill flow with their structure being dynamically dependent upon local flow conditions. They have often a complex structure of two or more sedimentational layers.
- Afterflow seals are extremely thin skin features with strong continuous orientation of clay particles formed by fine particle deposition after rain cessation and not by raindrop impact mechanisms (Slattery and Bryan, 1994).

Crusts are layers that have a greater density, higher shear strength and lower saturated hydraulic conductivity. They are sometimes more water-repellant than the underlying soil surface. Surface sealings are characterized by low infiltration rates and high runoff rates that may cause soil erosion. The ambivalent effect of seal formation is that seal development increases the shear strength of the soil surface and thus reduces soil detachment, but seal formation also increases runoff which in turn increases the transport capacity for entrained material. Once runoff starts, the presence of a crust increases the erosive power of the overland flow and hence soil detachment (Kazman et al., 1983; Bradford et al., 1987; Moore and Singer, 1990; Levy et al., 1994).

Agassi et al. (1981), Kazman et al. (1983), Gal et al. (1984), Radcliffe et al. (1991), Bohl and Roth (1993) and Levy et al. (1994) reported that low electrolyte concentration and high exchangeable sodium percentage (ESP) lead to seal formation. ESP more than 15% reduces seal conductivity. Texture with clay content of approximately 20% or more affects seal conductivity.

Surface sealing is a dynamic and complex process which may involve many factors and sub-processes. Crust formation may often involve significant interaction between soil and percolating, as well as physical, processes (Slattery and Bryan, 1994). Data from extensive testing with a wide range of soil types are needed to assess the general applicability of current concepts on sealing (Slattery and Bryan, 1994). Many experiments on seal formation have been conducted in laboratories. In contrast, still little information is available with respect to the formation of surface seal under natural rainfall conditions in the fields (Bohl and Roth, 1993).

(3) Runoff

When the rainfall intensity is higher than the infiltration velocity into the soil, there is excess water accumulating on the soil surface. After the infiltration is satisfied, water begins to fill the depressions on the soil surface. This storage is known as depression storage. As the depressions are being filled, surface overland flow begins. Overland flow occurs at the rate of rainfall intensity minus infiltration rate. This difference is termed "rainfall excess".

The excess rainfall or effective rainfall is neither retained on the land surface, nor infiltrated into the soil. After flowing across the watershed surface, excess rainfall becomes direct runoff at the watershed outlet.

The runoff is that portion of the precipitation on an area, which is discharged from the area through stream channels. The part which is lost without entering the soil is called surface runoff, and the part which enters the soil before reaching the stream is called groundwater runoff or seepage flow or base flow from groundwater (Soil Science Society of American Journal, 1987). Before runoff occurs, rainfall has to satisfy the demands of evaporation, interception, infiltration, surface storage, surface detention and channel detention. One distinguishes the time from the start of rainfall to ponding and the time to overland flow.

There are two kinds of situation in which runoff occurs. The first is that of saturation excess. Water infiltrates to the water table, which then rises. When the water table reaches the surface, the soil is saturated throughout and any additional rain received on the soil surface simply runs off (Dunne, 1978). The second mechanism causing overland flow is that the rain falls faster than the rate at which it can infiltrate through the surface of the soil, and the rate of runoff is then the difference between the two (Horton, 1933).

For the water flow over any surface, a certain depth of water is required; this is the detention depth. As the flow moves into defined channels, there is a similar build-up of water in channel detention. When the soil is saturated, all rainfall water (minus saturated infiltration) flows over the soil surface. This is called saturation overland flow. When the rainfall ceases, runoff continues for a certain time before it stops; the quantity of runoff water discharged during that period is called "afterflow". It is equal to surface detention minus afterflow infiltration.

Factors influencing runoff rates and amounts are rainfall characteristics, soil surface conditions, including basal plant cover, and soil type. Many authors have investigated the influence of organic matter content, iron oxides, clay mineralogy, texture and exchangeable cations on runoff generation. Soil moisture content, crust formation and soil properties that affect crust formation, influence runoff (Bernett and Rogers, 1966; Agassi et al., 1981; Kazman et al., 1983; Truman and Bradford, 1990; Levy et al., 1994).

(4) Interrill erosion

Interrill erosion is (1) the removal of a fairly uniform layer of soil on a multitude of relatively small areas by splash detachment due to raindrop impacts, and (2) transport of particles by subsequent flowing runoff. It is a slow and mostly inconspicuous process. It may involve (1) detachment of soil material from the soil surface by raindrop impacts, (2) detachment by flow, and (3) transport of the resulting sediment by flowing runoff. The detachment capacity of interrill flow is small because of its low velocity. Most of the sediment removed from the interrill area is transported further by more concentrated overland flow (Young and Wiersma, 1973; Nearing, 1991; Levy et al., 1994).

The processes and rate of interrill erosion are extremely complex and varied. They depend both on soil external factors, such as rainfall intensity, raindrop size and the presence or absence of wind influence, and on intrinsic factors, such as soil texture, aggregation characteristics, surface roughness, susceptibility to crusting, and the presence and density of organic debris (Bryan, 1987).

Interrill erosion operates when, apart from splash detachment, overland flow has little detaching or transporting power. The most important mechanism for particle entrainment by thin flows is turbulence induced in the flow by raindrop impact. The erosion rate is not controlled simply by the raindrop detachment rate. Raindrop detachment may be a pre-requisite for erosion, but the proportion of raindrop-detached sediment that is eroded depends on the availability of competent overland flow to transport it. Detachment rates depend on the availability of loose and detachable particles (Parsons et al., 1994). Therefore, ranking of soils according to the amount of splash detached by raindrop impact will differ from a ranking according to the amount of soil material transported from an interrill area by surface flow. In other words, splash by raindrop impact is not an index of interrill soil loss (Bradford and Huang, 1993).

Selective entrainment tends to remove the finer particles, while raindrop impacts and slaking will cause soil dispersion and reduction of surface aggregate size. The overland flow is often coloured by material in suspension. Clay particles are carried in suspension. Larger particles like silt, sand, very fine aggregates and gravel, are transported by a process of saltation, rolling or sliding.

Interrill erosion is sometimes leading to rill erosion in the form of several broad, flat, shallow flow channels or braids, with deposition and entrainment within the flow lines. This is the evidence that the supply of detached sediment exceeds the capacity of the overland flow to transport it. The velocity and the erosive power of water flowing over the soil surface increase with the depth of flow. Its volume will increase rapidly in the case of high rain intensities and/or sealing soils.

Sandy and clayey materials are generally relatively resistant to removal by water. The former because the grains are too coarse to be transported easily and because they often provide the proper conditions for high infiltration which reduces the runoff, and the latter because its relatively great cohesion and stable porosity. These textures provide the possibility for sustained infiltration, except in swelling clay soils which become rather impermeable soon after wetting starts.

Roels (1984), after research in the Ardeche area, has pointed out some interrill erosion characteristics. They are as follows:

- interrill flow path lengths vary considerably both with respect to location and time. On rough slopes they may have lengths of up to about ten meters;
- the intensity of interrill erosion is only slightly affected by location on the slope; and
- detachment by interrill flow is negligible because of the hydraulic roughness. The capacity of the flow to transport detached particles is assumed to be limited.

Interrill erosion is a slow and mostly inconspicuous process. It operates, however, over large areas of the land and generally causes most of the soil loss. Denudation occurs rather than incision.

(5) Rill erosion

A rill is a very small, intermittent water channel with steep sides, usually only several centimeters deep and, hence, no obstacle to tillage operations (Soil Science Society of American Journal, 1987). Rill erosion is the removal of soil by water from very small, intermittent channels where there is an initial concentration of overland flow. Rill erosion occurs when these very small channels have become sufficiently large and stable to be seen.

Torri (1987), Rauws and Govers (1988), Crouch and Novruzzi (1989) and Govers (1991) have reported that rills can only develop when the scouring power of the overland flow exceeds the shear resistance of the soil. The transporting capacity of the overland flow carries sediment coming into the flowpath from the interrill areas.

The velocity of flow is determined largely by the angle of the slope, the flow path winding, bed and wall roughness. Its volume depends on rain intensity, the length of the slope and soil infiltration, as well as soil surface storage. Overland flow concentrated in flow lines due to local concentration becomes the dominant detaching and transporting agent.

Styczen and Nielsen (1989) have found five main phases in the rill erosion process: rill initiation/development of protorills, headcut erosion, addition of interrill material to the material eroded from rill bottom and sides, tail-erosion, wall collapse and erosion of this material.

- Rill initiation/development of protorills: rill initiation on bare soil depends on the ratio of shear stress to shear strength. Rills start when the shear strength or soil cohesion has been exceeded. When the rainfall intensities exceed the infiltration capacity, runoff concentrates in non-permanent interrill flow paths, which under storm conditions may eventually become permanent and result in the development of protorills.
- Headcut erosion: most of the runoff is now flowing in the well-defined channels, although they are still very small. Turbulence becomes more pronounced around the ripples on the bed. The ripples on the bed tend to grow in size (Merritt, 1984).

- Addition of material and erosion of bottom and sides: in the rill, several things may happen simultaneously. Water may enter the rill from the sides loaded with an interrill sediment concentration, and erosion may take place on the rill bottom and rill sides. Sediment is transported from the sides to the bottom, and the rill will have a tendency to widen out. The depth of erosion will be erosion minus sedimentation. The evolution of the rill sidewall is not only dependent on rill depth but mainly on the mechanical and hydrodynamical properties of the different soil layers. When saturation of a plow layer with bad structural characteristics occurs, mass movement can affect rill sidewalls over a depth of several decimeters. When the soil material has a better structure, rill walls recede dominantly by fall (favoured by crack formation) and shallow sliding (Govers, 1987).
- Rill tail erosion: rill will erode an amount of soil which is a function of the difference between the actual sediment load and the new transport capacity when the rill meets the surface. The downslope evolution of the rill is mainly a function of the slope.
- Wall collapse: the wall material above the eroded part is expected to fall down into the rill, which widens the rill. Sediment entrained from a rill is derived from subsurface horizons or parent material. Both denudation and incision play a role in rill erosion.

In many cases, rill erosion is a short transition stage preceding gully erosion.

(6) Gully erosion

A gully is a channel resulting from erosion and caused by a concentrated but intermittent flow of water usually during and immediately following heavy rains. It is deep enough to interfere with and not to be obliterated by normal tillage operations (Soil Science Society of American Journal, 1987). Thus, gully erosion is often an advanced stage of rill erosion, much as rill erosion is often an advanced stage of interrill erosion.

The rate of gully erosion depends on runoff-producing characteristics of a slope or landform (amount, concentration and speed), the drainage area, soil characteristics (resistance of the soil to erosion), the alignment, size and shape of the gully, the slope in the channel and the vegetation. Gully erosion mostly occurs when the subsoil consists of loose material

(Govers, 1987). In the development of a gully, many processes may take place either simultaneously or during different periods of its growth. The most important processes that take place are: waterfall erosion at the gully head, channel erosion caused by water flowing through the gully, and slides or mass movement of soil in the gully. Four stages of gully development are generally recognized (Glenn, 1981):

- Channel erosion by scour of the topsoil. Formation of a deep rill results from lateral water concentration on the slope. This stage proceeds slowly where the topsoil is fairly resistant to erosion. Control at that stage is easily possible.
- Upstream movement of the gully head and enlargement of the gully width and depth. The gully cuts into the B and C horizons. A weak parent material is rapidly removed. A waterfall often develops where the flow plunges from the upstream segment under stage 1, to the eroded channel below. Headward erosion of the gully may occur as a result of mass movement from the walls. Seepage may also cause further headward erosion. The gully becomes difficult to control.
- The channel tends to become graded according to some local base level. The slopes of the walls are reduced in steepness and the gully widens. The headward catchment area becomes smaller and provides less runoff. At that stage, vegetation begins to grow in the channel.
- Stabilization of the gully. The channel reaches a stable gradient, gully walls reach a stable slope, vegetation begins to grow in sufficient abundance to anchor the soil and permit development of new soils.

During the stages 2 and 3, the gully head progresses towards the local divide, and the rate of runoff into the gully head decreases because the drainage area is decreasing. A gully cross-section can be U or V-shaped, depending upon the constitution of the soil profile, rainfall characteristics, and the age of the gully. A U-shaped gully may be found where both the surface soil and the subsoil are easily eroded; a V-shaped gully may develop where the subsoil is resistant to erosion. In general, the gully form may reveal properties of the material, such as permeability and coherence. It may reflect the balance between the denudation and the incision processes.

3.2.3 Distribution of erosion features on the relief

The ideal relief form, on which erosion features often develop naturally and can be studied, is a hillslope. A hillslope offers subdivisions which are meaningful for all kinds of erosion processes and their features. It shows erosion features and corresponding deposition features and leaching processes, defined by type and intensity along the relief, with respect to climatic conditions, soil characteristics, topography, land use and management. The subdivision of a hillslope may yield the following landforms: summit, shoulder, backslope and footslope.

At the begining of the rainfall and on bare soil, splash erosion is dominant over the whole hillslope. When rainfall intensities exceed infiltration rate or when the soil is saturated, runoff starts. Because of the flat topography of the summit, runoff moves over a plane surface. As the depth of water increases, splash erosion decreases.

Runoff moves from the summit to the shoulder on a spur flow. Because of the change in topography from the flat summit to the convex shoulder, runoff gains erosive power and removes soil more or less in uniform thin layers. Interrill erosion is the most important erosion process here.

Runoff generation from the backslope and run-on from the summit and the shoulder enhance the erosive power of runoff. If the backslope is steep enough, there is a tendency of fast disposal of the overland flow that will concentrate depending upon rainfall characteristics, soil properties, and vegetative cover. This favours splash erosion, interrill erosion and rill erosion.

The position of a gully on the hillslope depends on the type of gully formation. Three types of gully and, consequently, three different gully distributions on the hillslope have been described by De Oleivera (1985).

- In the first type, a kind of channel connected to the main drainage system appears to develop by headward expansion. The initiation of channels seems to be related to seepage erosion caused by the creation of a free face downslope. Seepage erosion is the dominant process. The gully develops by the collapsing of lateral walls in a complex way, controlled by the stratigraphical distribution of colluvial and alluvial deposits. Gullies are positioned on the footslope.

- The second type is related to the traditional Hortonian overland flow. Gullies show a network of upward rills caused by collapsed cattle steps or concentrated overland flow on the divides and lateral slopes. Concentrated overland flow plays a role mainly in the excavation and widening of the channel. The process is a combination of concentrated overland flow and mass movement. Gullies occupy shoulder and backslope.
- The third gully type is the combination of the two earlier ones. Erosion reaches the last degree of expansion upward. Only the upper part of the gully remains active. It is the final stage in gully evolution. Gullies occupy the shoulder, backslope and footslope.

3.3 EROSION PREDICTION MODELS

3.3.1 Assessment of soil erosion

Soil erosion has been measured at different scales using various equipments. These scales can be grouped into three levels according to the objectives: micro-plot level, plot level and watershed level.

At the micro-plot level (0.5 to 2 m^2), erosion works are conducted under controlled conditions to study erosion processes such as splash or interrill erosion and the effects of soil properties on them. The study allows evaluation of the relative erodibility of different soils. The research can be conducted on the field or in the laboratory using rainfall simulators. A wide range of rainfall simulators is commercially available. Splashed sediment traps or collecting troughs are the main equipment used.

Studies at plot level are mainly conducted under natural conditions. The scale varies from few square meters to few hectares. The standard plot (Wischmeier plot) is 40 m^2 (22.6m x 1.8m). Its objective is to evaluate standard erodibility. Soil erosion research at the field scale allows evaluation of the effects of farming practices, land use systems or topographic factors. Various equipments and techniques are available. For instance, hydrologic structures with crest weirs are used to measure runoff and sediment concentration at the watershed outlet. Radioisotopes and other tracers are suitable to identify the source of sediment over the watershed (Rietchiet et al., 1974). Other methods are measuring changes in the soil surface: remnants of the original soil surface, pedestals formed by stone covers, exposed tree roots, buried nails and stakes.

The study of soil erosion at the level of watershed involves hundreds to thousands of square kilometers of area and deals with streams and river basins. It is used to assess denudation rates of major river basins, mountain systems, continents, and ecological regions. For example, Gregory and Walling (1973) reported that the denudation rates are 27, 35, 45, 63, 96 and 600 t/km^2/yr for Africa, Europe, Australia, South America and Asia, respectively. The major parameters that are measured are stage or water level, velocity, discharge, sediment concentration, and their variation through time. Several types of equipment are commercially available: floats, pendulum current meter, dyes, tracers, photoelectric turbidity meters and neutron or gamma probe devices.

3.3.2 Concepts of soil erodibility

Soil erodibility has been defined as the inherent or natural tendency of soils to erode at different rates due to differences in soil properties (Wischmeier and Mannering, 1967; Le Bissonnais and Singer, 1993). Hydrologic processes are needed to drive erosion processes. As a consequence, soil erodibility represents both the susceptibility of the soil to erosion and the amount and rate of runoff, as measured under standard unit plot conditions (USDA-SCS, 1993). Soil erodibility is a major factor in erosion prediction and land-use planning, that depends both on the infiltration capacity and on the capacity of soil particles to resist detachment and transport by runoff flow (Wischmeier and Mannering, 1969). Its magnitude varies with soil characteristics.

Middleton (1930) developed an erodibility index based on soil dispersion properties. Gibbs (1945), Resendiz (1977) and Lebron et al. (1994) have reported that the clay activity index (plasticity/clay% by weight) is an appropriate index to determine the stability of soils.

Aitchison (1996) proposed the use of clay dispersity as an index to classify the susceptibility of soils to erosion. Unfortunately, none of these has shown to be a satisfactory measure of erodibility for a range of soils in the tropics (Lal, 1981).

The well known equation to predict soil erodibility is the nomograph of the Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978), where the soil erodibility factor is represented by K. Within the USLE framework, erodibility is defined as the long-term average rate of erosion per unit of rainfall erosivity. This definition does not consider the contribution of rill and interrill erosion, and variation of these processes may be the major cause of observed year-to-year variation of the K factor (Loch and Pocknee, 1995).

Many recent studies have drawn attention to the fact that indices of soil erodibility show pronounced seasonal variations (Imeson and Verstraten, 1986). Researchers have recognized the importance of developing models that predict soil loss on a storm-by-storm basis. Therefore, soil loss predictions relating individual storms are needed, and lumped equations such as the USLE are unsuitable for making such predictions (Roels, 1984). Major improvements are likely to originate from erosion prediction models based on fundamental hydrologic and erosion processes (Foster, 1990). Much work has already been done on this approach, but more remains to be done before a general deterministic model of erosion is developed (Le Bissonnais, 1993).

Lal and Elliot (1994) have reported that interrill erodibility could be estimated by the following equations:

- for clay more than 35 %: $k_i/10^6 = 2.67 - 0.115\ (\text{In}(18 - \text{Stab})^2)$, (if $17 < \text{Stab} < 19$, then $K_i = 2.67$)
- for clay less than or equal to 35 %: $k_i/10^6 = -2.92 - 2.71(\text{WDClay/Clay}) - 0.5\text{Mg} + 0.10\text{WDClay} + 4.19(\text{Clay/Fe+Al}) + 1.24\text{Cond}$

where: K_i is the interrill erodibility (kg sec m^{-4}); clay is the clay content, in %; Stab is the stability of aggregates < 0.25 mm, in %; WDclay is the water dispersible clay, in %; Mg is magnesium content, meq/100 g; Fe is the iron content, meq/100 g; Al is the aluminum content, meq/100 g; Cond is the electrical conductivity of a saturated paste of soil.

Many researchers have defined interrill erodibility (K_i) in a specific way and calculated it empirically by a specific equation. No standard procedure or set of conditions exits for determining or calculating K_i. The true K_i is the one defined by a specific empirical equation in which all other variables in the equation are measured under field conditions at a given time of the year (Truman and Bradford, 1995).

3.3.3 Soil loss prediction models

Pioneer research work on soil erosion was carried out by the soil scientist Wollyn, between 1877 and 1895 (Baver, 1939). He studied, on small plots, the effects of mulches, soil type and slope on soil erosion (Hudson, 1996). Zingg (1940) studied the effect of slope. He found that doubling the degree of slope increased soil loss by 2.6 to 2.8 times. An empirical model relating slope steepness to erosion potential was derived in an exponential function form. Fournier (1960) and Douglas (1967) developed other empirical models relating sediment yield to the characteristics of rainfall, runoff and watershed. The most leading works on soil erosion have been carried out in the United States of America and Western Europe. Many soil loss prediction models have been developed and differ from one another according to their objectives and scales. They can be grouped into empirical, process-based, productivity and watershed models. Lal (1990) and Hudson (1996) described them as follows.

(1) Empirical or "black-box" models

Empirical models are derived from observations and experiments, not from theory. The term "black-box" is used because the models operate in such a way that inputs go into one side of the equation and the answer is the output on the other side of the equation, and one does not need to know or understand what happens inside the black box. Some of the most commonly used models are described below.

- The Universal Soil Loss Equation (USLE) developed by Wischmeier and Smith (1978) is the most used prediction model. The equation is presented in the form:

$$A = R x K x LS x C x P$$

where A is the average annual soil loss in tons per acre, R is the erosive forces of rainfall, K is the soil erodibility factor, L is the slope length factor, S is the slope gradient factor, C is the crop management factor, and P is the conservation practice factor.

- The Revised Universal Soil Loss Equation (RUSLE). There is a discrepancy between measured and estimated results when applying the USLE. Wandelaar (1978) reported that using the USLE, predicted erosion was more than that measured on the field. The RUSLE was then developed to accommodate new ideas, results and practices that are not found in the USLE.

Elwell (1977) developed the Soil Loss Estimation Model for South Africa (SLEMSA) to predict soil loss in Zimbabwe. Basically, the model follows the USLE structure.

(2) Process-based or physically-based models

Process-based models explain mathematically each physical process and then combine the separate effects. Because of the great amount of data and mathematical calculations needed, such models are only operated through computers. Many models have been developed. The major ones are as follows:

- European Soil Erosion Model (EUROSEM). Its objective is to assess erosion and pollution at field and catchment scales. It is a useful tool for selecting soil protection measures.
- Chemicals, Runoff and Erosion from Agricultural Management System (CREAMS). This model allows the comparison of the effect of different practices on an event basis.
- Areal Non-point Source Watershed Environment Response Simulation (ANSWERS). This model evaluates sediment yield and the cost effectiveness of possible land use at watershed scale. It has a huge database which requires the use of computers.
- Water Erosion Prediction Project (WEPP). The main objective of WEPP is to develop a new generation of erosion prediction technology. It should be applicable to different scales and land uses. The soil-based component of the WEPP improves upon the

lumped mean annual K-factor approach of the USLE and distinguishes between rill and interrill erodibility. Interrill erosion equations, that represent the relation between the net soil loss per unit area and the erosivity factor, have been developed (Roels, 1984). Such equations are in the form of:

$$\text{LogGir} = \text{aLogEAIM} + \text{b}$$

where: Gir is the sediment load in the source area; EAIM (in mm^2/h) is the product of the excess rainfall amount (EA in mm) and the maximum 5-minute intensity (IM in mm/h).

Soil erosion models usually represent interril erosion empirically as a power function (Meyer, 1981; Line and Meyer, 1988; Meyer and Harmon, 1989; Kinnell, 1991):

$$E = aI^b \qquad (1)$$

$$E = K_{ii}I^2 \qquad (2)$$

$$E = K_{iq}Iq \qquad (3)$$

where E is the interrill erosion rate, a and b are constants related to soil properties, I is the rainfall intensity, K_{ii} and K_{iq} are interrill erodibility parameters, and q is the flow discharge.

(3) Productivity models

Productivity models estimate the loss of productivity. The common ones are as follows:

- Erosion Productivity Impact Calculator (EPIC). It is a combination of empirical and physically-based components. A huge amount of data is required to operate. The model can estimate changes in production on a long-term basis.
- Productivity Index Model. The model is designed to estimate long-term effects of soil erosion. A large input data is needed to run the model.

3.4 SOIL CONSERVATION MEASURES

3.4.1 Damage caused by soil erosion

Accelerated erosion proceeds more rapidly than geological erosion and takes place after man has disturbed the natural balance between climate and natural resources (soil, vegetation) by introducing landuse activities. Once the soil is lost, it is difficult to renew it within the forseeable future. It takes hundreds to thousands of years to develop the equivalent of a 5 cm-layer of fertile soil. In contrast, soil erosion can be drastic and rapid in such a way that the soil formed over hundreds of years is washed away in a single rainfall event (Lal, 1990). Shallow (1956) reported that in the Cameroon Highlands, deforestation for any purpose increases soil erosion rate from 0.2 t/ha/yr under natural forest to 4.9 t/ha/yr under mature coffee and to 7.3 t/ha/yr under vegetables. It is argued that 2 million hectares of arable land is lost annually due to severe soil erosion and erosion-induced soil degradation. Lowdermilk (1953) and Olson (1981) pointed out that the effect of soil erosion is considered to have caused the downfall of some of the once-thriving ancient civilizations, for examples the Roman Empire, Mesopotamia (present-day Iraq) or the Negev desert.

The erosion issue originates from two sources. Firstly, it stems from the detrimental on-farm effects of erosion regarding for instance soil productivity decline by removal of plant nutrients and organic matter, increased compaction, and increased runoff. Secondly, erosion problem also rises from the harmful off-site effects such as silting of reservoirs, lakes, irrigation canals, streams and coastal areas, and flooding of land. Some exemples are given: increase of sediment concentration in the Perkerra river in Kenya (Dunne, 1975); need to increase dam heights on some Morocco's dams to maintain the storage capacity (FAO, 1993); flood disasters in India due to the deforestation of the Himalayas (Nill et al., 1996). High runoff leads to loss of water from the watershed, which lowers the groundwater level and causes water shortage in the wells. Pesticides and chemicals dissolved in runoff or contained in the sediment may cause pollution problem.

3.4.2 Soil loss tolerance

Soil loss tolerance limits define the soil loss amounts, which are tolerable to maintain economically and continuously the sustainability of the soil. Within these limits, soil erosion and soil formation processes are in equilibrium. The soil loss tolerance depends on the soil type. On very deep and homogeneous soils, the effects of erosion will be less pronounced than on shallow soils encountered on highlands of semiarid zones or on highly weathered soils whose nutrient storage and availability depend largely on the organic matter of the surface layer (Nill et al., 1996).

Yield decreases due to soil erosion may depend also on the type of crop. Mbagwu et al. (1984) showed the removal of a 5 cm-thick soil surface layer reduced maize yields by 95% and 52% on Ultisols and Alfisols, respectively. Cowpea yields were reduced by 63% and 22% on Ultisols and Alfisols, respectively.

The maximum annual soil loss rate in the United States is set to 11 t/ha/year. Tolerance values for tropical soils have not yet been formulated at the international level (Nill et al., 1996). Nevertheless, Hurni (1980), Lal (1983) and Hudson (1986) established annual soil loss tolerance limits which vary between 0.2 and 11 t/ha.

3.4.3 Soil conservation practices

The reduction in fertility has been masked by increased use of fertilizers, pesticides, herbicides, crop hybrids and mechanization, at a much increased cost (Foster, 1977). Modern soil conservation techniques can almost reduce the speed of the erosion process to a degree similar to that of natural erosion, but this requires that the soil be appropriate (Hudson, 1996). There are many erosion control measures. A grouping of these according to their objectives yields three main soil conservation practices, including mechanical protection measures, biological measures and erosion control through land husbandry.

(1) Mechanical protection measures

Mechanical protection measures concern all the methods which involve earth moving. Their objective is to modify the soil slope, to contain erosion or to control runoff (absorb, contain or multiply runoff). The major ones are: bench terraces, hillside ditches, individual basins, orchard terraces, intermittent terraces, absorption terraces, contour bunds, deep tillage, ripping and subsoiling.

(2) Biological measures

Biological measures are related to the crop characteristics or crop management. The objective is to reduce raindrop impact by maintaining a good ground cover. The main crop characteristics required are early planting, good stand and optimum plant population, balanced fertilizer applications, adequate weed, insect and disease control, and more utilization of on-farm inputs such as mulch and manure.

(3) Erosion control through land husbandry

Erosion control through land husbandry is a new approach in erosion control measures. The objective is to offer better land use alternatives, taking into account biophysical factors and socio-economic circumstances of the farmers. The land use should at the same time reduce soil erosion and increase production at an acceptable cost. The major farming practices are listed as follows:

- Farming on grade: the practice enhances infiltration by returning crop residues and allows surplus runoff at low velocities.
- Strip cropping: it reduces runoff velocities on sloping land without any bank or drain.
- Rotation: it is a well established practice in the tropics. The objective is to improve fertility by introducing different crop types into the rotation, for instance cereals/legumes.
- Shifting cultivation: the objective is to regenerate naturally the soil fertility by fallow periods. The fallow period can be shortened by planting grasses or legumes. But, the practice is no more sustainable and becomes damaging with population increase which causes pressure on the land, short fallow periods and reduction of arable land.
- Mixed cropping: it is a combination of crops with different planting times and different length of growing periods and harvesting. The practice allows more or less a permanent ground cover, mainly in humid areas.
- Agroforestry: the method is a kind of mixed cropping where agriculture is carried out between trees. However, the development of agroforestry requires that a number of problems be overcome and some requirements be fulfilled. For instance, the interest of farmers for trees should be shown, the practice should be both useful and within the physical and managerial capacities of the farmers, the land tenure system and land use rights should be adequate, and competition for moisture and light between crops and trees should be low (Hudson, 1996).

3.5 MAPPING OF SOIL EROSION

3.5.1 Mapping of soil erosion at watershed scale

Soil erosion is an environmental problem. Environmental emergencies often have effects that are distributed over the earth's surface. As a result, maps are usually the most effective way to portray the impact of these emergencies. Maps are indispensable tools for identifying and representing locations, distributions and spatial variations. Maps are explicitly designed to capture or preserve the geographical (spatial) dimensions of environmental features in a concrete form (Muehrcke, 1986).

Soil erosion risk can be defined as the vulnerability of a soil to erode in space and time. As such it is a multidisciplinary study domain, because it involves many other geographical fields of study, including soil, geology, topography, vegetation, hydrology and land use. A soil erosion risk map can then be considered as an integrated map combining different maps. Time is relevant when dealing with soil erosion, because it is a rapidly changing environmental phenomenon. Soil erosion has negative effects on the environment, for it conflicts with the land resources sustainability concept. In fact, the environment should be protected (used) in such a condition and to such a degree that environmental capacities (the ability of the environment to perform its various functions) are maintained over time. The use of natural resources should be at least at levels sufficient to avoid future catastrophe, and at most at levels which give future generations the opportunity to enjoy an equal measure of environmental consumption (Jacobs, 1991). This implies that an integration of economic and ecological considerations in decision making should be achieved, and a production system that respects the obligation to preserve the ecological environment must be established (Allan and Sandra, 1991).

Planning is defined as making strategies. It is described as an organized, conscious attempt to select the best available alternative to achieve specific goals (Cowan, 1973; Annet, 1992). Castellano (1991) defined planning as a decision-making method, that leads to the transformation of a current situation into a more acceptable future situation by distributing scarce resources among multiple objectives to minimize costs and maximize benefits under a dynamic social equilibrium. As such, the essential task of planning is the definition of development possibilities to determine the most efficient use of existing natural and manmade resources (Kozlowski and Rosier, 1986). For soil conservation purposes, McDonald and Brown (1984) defined policies or rules that determine the allocation of a given land use to a particular area or planning unit: high historical value and high landscape amenity, undisturbed habitat, high levels of soil erodibility, water-supply catchment, and crown land.

The quantity of information involved in erosion risk assessment and land use planning exceeds the capacity of a manual system to effectively produce relevant information for decision making, whereas presenting geographical data on a map more quickly and more accurately is needed. An effective use of large volumes of data depends on the existence of an efficient system that can transform the data into usable information. Understanding interactions between different soil erosion factors and presenting the results in an easier way (map) should precede any planning, policy making or action.

Since some decades, geographic information systems (GIS) are becoming essential tools in this complex situation for analysing and graphically transforming knowledge about the world (Van Westen, 1994). It aims at preventing environmental degradation by giving decision-makers better information about the consequences that the misuse of land could have on the environment.

3.5.2 Mapping of soil erosion at plot and micro-plot scales

Erosion assessment is not an aim in itself, it should lead to soil and water conservation measures. For making recommendations on soil and water conservation, erosion rates alone do not help much. The site-specific erosion problems regarding for instance the type, extent, location and effects on crop yields, must be known to initiate conservation measures. Each soil has its own characteristics in erosion development. Two soils may generate similar soil loss, but they may show differences in coverage and distribution of actual damage.

In soil erosion studies, maps are produced to show erosion features in a certain area, but these maps do not show the horizontal distribution of actual erosion (Sterk and Stein, 1997). Such maps can help interpret the relation between spatial variation of some soil properties and erosion. Geostatistics offers methods for mapping changes in environmental variables by variogram modeling and kriging interpolation (Sterk and Stein, 1997; van Groenigen and Stein, 1997). The threshold distance beyond which erosion is considered to have substantially modified the relative homogeneity of a soil unit on a given area, can determine the design of soil erosion measures.

CHAPTER 4

METHODS AND TECHNIQUES

This chapter presents the methods and techniques applied in the research. The study involved three data sources: field observations and measurements, laboratory analyses and existing maps (geology, topography, soil). The methodological approach adopted in the study followed from the conceptual frame developed by López and Zinck (1991) (figure 4.1). The procedure allowed the explicit consideration of general inventory studies, field checks, cartographic modeling, statistical and geostatistical analysis. The research included five phases. The first phase consisted of undertaking a conventional soil survey for the identification of the soil classes with their degrees of erosion severity at regional level. The second phase focused on the assessment of soil erosion at plot scale for the design of effective soil conservation measures. The third phase examined the interactions among different erosion parameters, for the development of a local model of interrill erosion at micro-plot scale (figure 4.2). The fourth phase emphasized the rehabilitation of severely eroded soils to increase the current and potential capability of the area to provide goods through agricultural and livestock uses. The last phase dealt with integrating the research results to achieve sound understanding of land use planning for conservation of the rural environment. Three spatial scales of study were concerned: the watershed scale, the plot scale and the micro-plot scale.

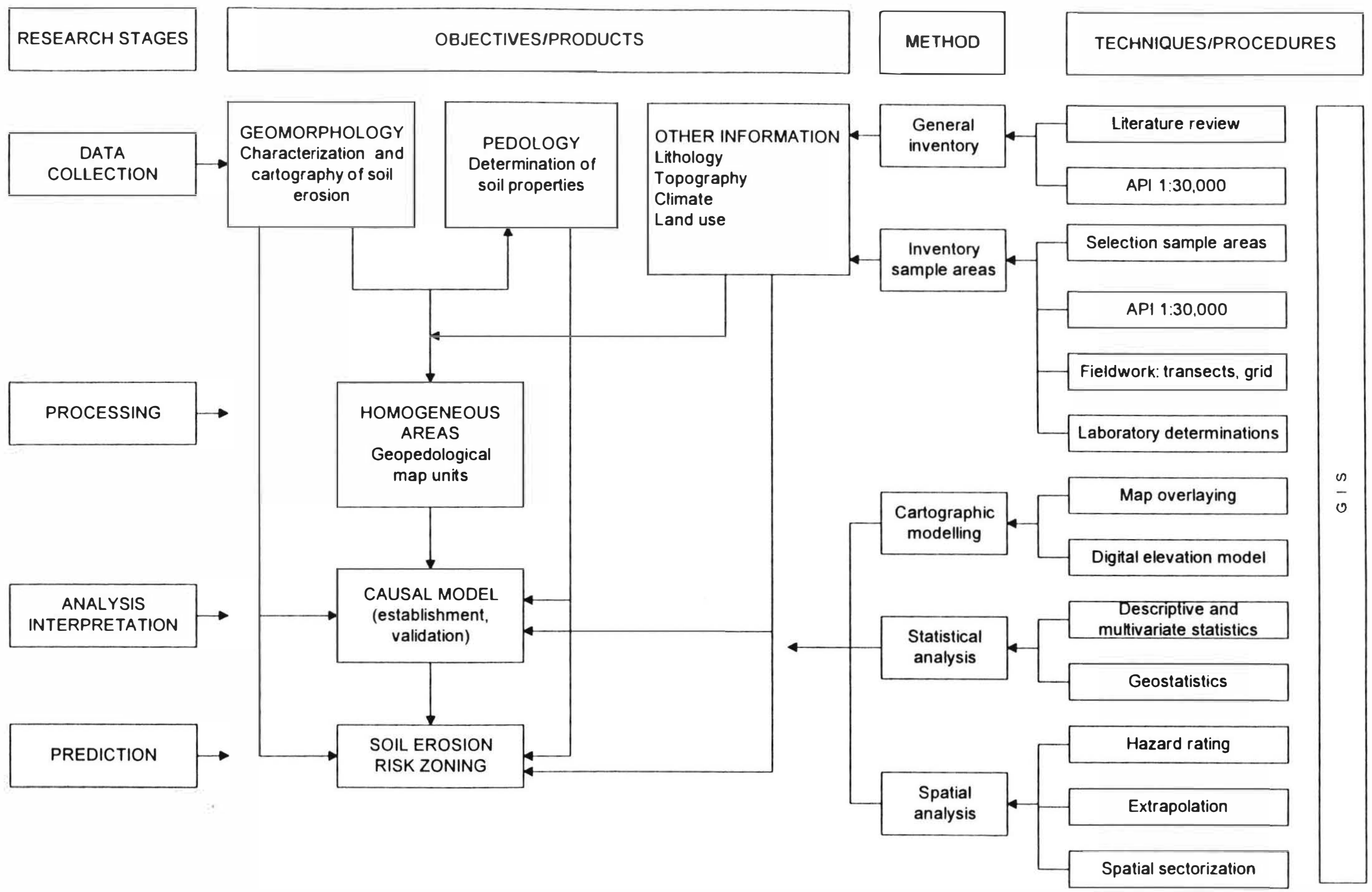


Figure 2.1 Conceptual frame (López and Zinck, 1991)

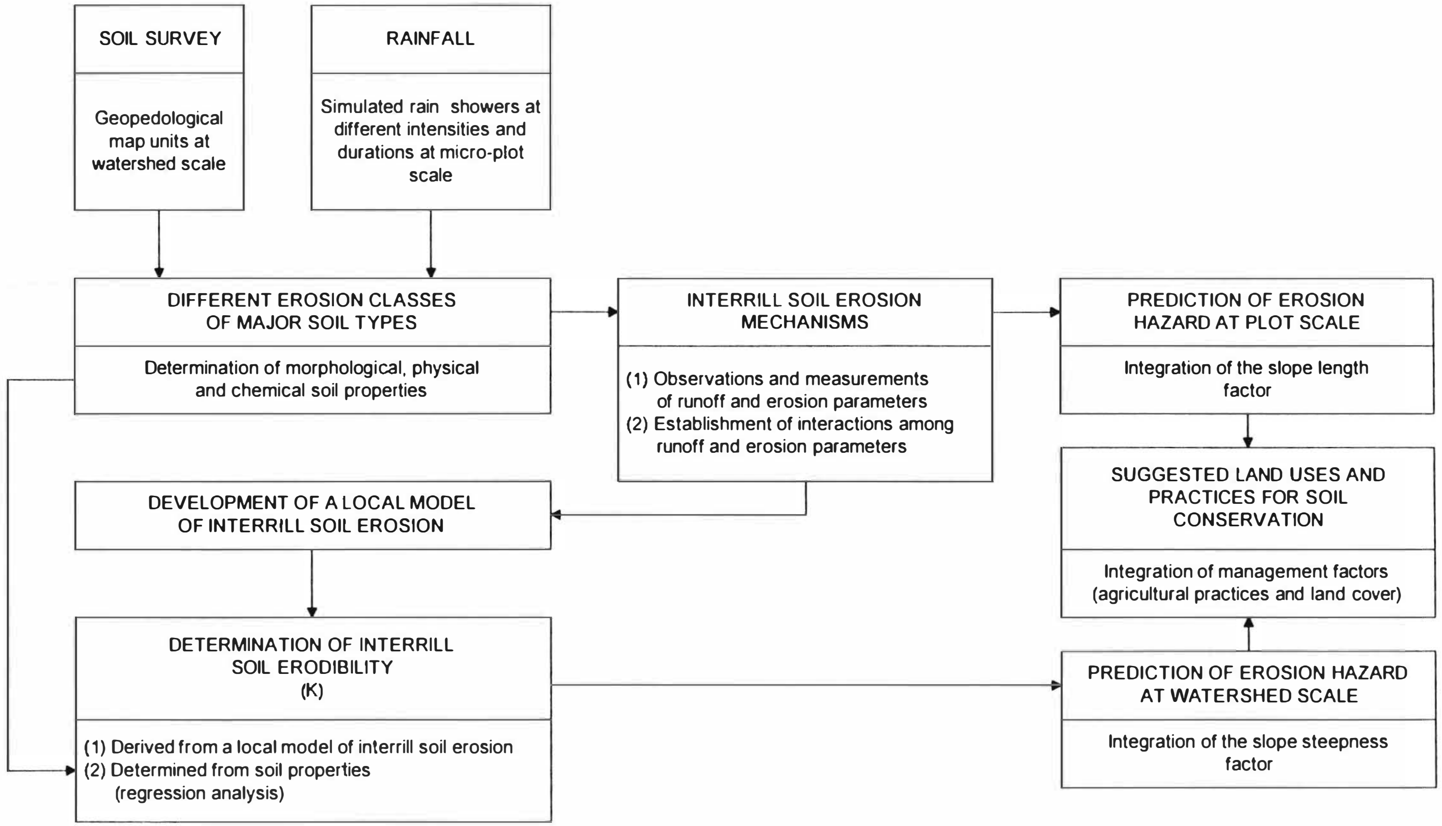


Figure 4.2 Flowchart of the procedure for determination of interrill soil erodibility

4.1 DATA COLLECTION

4.1.1 Field investigations at watershed scale

(1) Farming systems analysis

Investigations on the variability and distribution of farming systems were conducted to understand and assess the influence of land uses and local knowledge on soil conservation measures. Interviews with 120 farmers were held individually and field observations were carried out to identify the farming system types. Classification criteria included the type of the human activity, the type of crop or vegetation, the duration of the farm, agricultural practices, soil conservation practices and the productive capacity of the land. Most of the field investigations were done in sample areas and the results were extrapolated to the whole study area.

Two levels of detail were considered. At the first level, attention was paid to the variability and distribution of farming systems in relation to seasons, soil types and crop characteristics in a global context. The second level of detail emphasized the variability of land uses, organization and allocation of the land according to different erosion classes within major soil classes.

(2) Soil survey

Preliminary work was carried out in the office, including interpretation of aerial photographs at scale of 1:30,000 dated June 1993 with a binocular stereoscope, and examination of existing maps. Base materials consisted of a topographic map at scale of 1:50,000, a geological map at scale of 1:1,000,000, a vegetation map and soil maps at scale of 1:200,000 and 1:50,000 (Letouzey, 1968; Segalen and Vallerie, 1962; Sieffermann and Martin, 1963; Pontanier and Kotto-Samé, 1982).

Three sample areas covering about 30% of the study area were selected and analyzed according to genetic keys that control soil variations, such as geoform, parent material, vegetation and natural drainage. Accessibility to and proximity of water supply point for rainfall simulation experiments also influenced the location of the sample areas.

(a) Variability and distribution of soil types

Variability and distribution of the soil classes were mainly analyzed on sample areas. The main activities involved checking of the boundary accuracy between map units and soil description. Within each map unit of the sample areas, ten mini-pits were described (table 4.1). Soil characteristics were averaged. A representative profile was described where a mini-pit presented characteristics similar to the averaged soil characteristic values. Soil profiles were described according to the FAO guidelines (FAO, 1990). Soils were classified according to CPCS (1967), Soil Taxonomy (USDA, 1996) and FAO (FAO-WRB, 1998). Soil samples were taken for determination of physical and chemical properties at the soil laboratory of IRAD-Yaoundé (Cameroon).

(b) Variability and distribution of erosion classes

Surface features were used to distinguish different erosion classes. The main features were: the presence of rills and gullies, color, accumulation of coarse fragments (iron-manganese concretions, calcareous nodules, gravel and rock fragments) on the soil surface and in the topsoil layer (Rhoton et al., 1991; Kreznor et al., 1992). Land use also contributed to identify erosion phases. Four erosion classes were identified and described according to the criteria reported by Van Wambeke (1986) and the Soil Survey Manual (1996): slightly, moderately, severely and extremely eroded soils. The study was mainly conducted in the sample areas. Some check points were made out of the sample areas for confirmation of the map units before extrapolation of the results to the whole study area. A final soil map at the scale of 1:50,000 covering about 80,000 hectares, with map units classified at the level of erosion phases, was produced.

(c) Soil variability in selected map units

Observations and some simple field tests were carried out on twelve selected map units to assess the variability of the soil properties within and between map units. Observations were done along three directions with an angle of 120 degrees at 5 m intervals from the point where rainfall simulation experiments were performed. A total of 7 observations per transect and 21 observations per map unit were obtained (table 4.1). At each observation point, a short description of the topsoil layer was made. A composite of five soil samples collected from the topsoil layer was made at each observation point. A total of 21 composites per site was collected for determination of organic matter content, particle size and pH (water) at the soil laboratory of IRAD-Yaoundé (Cameroon).

Table 4.1 Field observations and soil sampling for conventional mapping and soil variability study

Investigation	Total map units	Observation type	Distance (m)	Observations per map unit	Total observations	Total sampling
Conventional mapping (sample areas)	29	Augering Mini-pit Modal profile	Variable Variable Variable	Variable 10 0 - 2	Variable 250 25	0 0 87
Soil variability	12	Mini-pit	5	21	252	252

4.1.2 Field investigations at plot scale

(1) Farming systems

Investigations on farming systems were conducted at plot scale to understand and assess the influence of land use and local knowledge on soil conservation measures about soil erosion in the Gawar area. Individual interviews were held with 120 farmers and field observations were carried out to identify the types of soil conservation measures that are applied at farm level.

(2) Spatial variability of erosion indicators

(a) Selection criteria

The variability and distribution of erosion features and crop characteristics, assuming that crop behaviour is an indicator of the effects of soil erosion, were studied to interpret the relationships between spatial variations of soil properties, crop characteristics and erosion. The study tested two hypotheses formulated from the results obtained at micro-plot level about the variations of the soil surface elevation points:

- small rates of decrease of the soil surface elevation points due to erosion cause pronounced erosion features only downslope;

- high rates of decrease of the soil surface elevation points due to erosion generate erosion features distributed all over the area.

Two sites, one on moderately eroded Lixisols and the other on moderately eroded Vertisols, were selected to conduct the experiments. The importance of choosing these soils is threefold:

- they represent situations of small rates of decrease of the soil surface elevation points (moderately eroded Lixisols) or high rates of decrease of the soil surface elevation points (moderately eroded Vertisols);
- they represent critical soils producing either considerable amounts of runoff (moderately eroded Lixisols) or considerable amount of soil loss (moderately eroded Vertisols);
- they are continuously used for cropping.

(b) Recording procedure

On each of the two soils, an area of 40 m x 104 m was delineated from the divide downslope. The general slope was 1% at each experimental site. Thus, both areas had similar topographic characteristics (position, slope length and slope steepness). Erosion features were measured and related incidental features such as crop characteristics were described.

Erosion indicators were recorded on a grid at 8 m intervals between observation points, generating 65 observation points per site. Additionally, 15 observation points were described at 2 m intervals to assess the variability at short distance. In total, 80 investigation points were obtained per experimental area (table 4.2). Each observation point covered about 4 m^2 to allow maximum recording of the indicators. At each observation point, the erosion indicators were recorded on a grid of 12 cm intervals. A total number of 289 cells per observation point were recorded.

Table 4.2 Field observations and soil sampling for distribution of erosion indicators

Soils	Features	Distance (m)	Total observations	Total per feature
Moderately eroded Lixisols	Soil properties: pH, organic matter, particle size, resisting clod, eroding clod, depression	8	65	80
		2	15	
	Management practice: dimensions of the ridge-furrow system	8	65	80
		2	15	
	Agronomic aspect: height of cotton plant	8	65	80
		2	15	
Moderately eroded Vertisols	Soil properties: pH, organic matter, particle size, cracked areas	8	65	80
		2	15	
	Agronomic aspect: height of sorghum, length and diameter of the ears	8	65	80
		2	15	

The dominant feature (> 50% area) occurring within each 12 x 12 cm-cell of a grid determined the classification of that cell. Each feature was expressed in area percentage. All the numbers were added to yield 100 %. The investigation of the erosion features was carried out at the moment of harvesting, when erosion development was at the last stage for that growing season.

(c) Indicators recorded on moderately eroded Lixisols

Cotton was cultivated on the moderately eroded Lixisols in a ridge-furrow system constructed parallel to the slope. At the time of planting, the ridge width was 70 cm, the furrow width was 30 cm and the ridge height was 20 cm. Cotton plants were located along the summit of the ridges. The distance interval between two consecutive cotton plants on a ridge was 35 cm and the distance between two consecutive ridges was approximately 100 cm.

Six types of soil surface features caused by soil erosion were identified, including original/resistant clods, eroded clods, prerills, rills, depressions and deposition/colluvium. Additionally, characteristics of the ridge-furrow system such as the width of the ridge, the width of the furrow and the depth of the furrow, were recorded. The height of cotton plants at each observation point was recorded.

Mini-pits were described at each observation point. The thickness of the topsoil layer was measured. A composite of five soil samples from the topsoil layer (0 – 5 cm) was collected at each observation point for determination of the organic matter content, particle size and pH (water).

(d) Indicators recorded on moderately eroded Vertisols

The experimental plot on moderately eroded Vertisols was under post rainy season sorghum (Muskwari) cultivation. Land clearing consisted of slash and burning. No particular land management was done during seedbed preparation. Sorghum plants were transplanted at 100 cm interval along lines separated 100 cm. There were three sorghum plants in each plant-hole, giving a density of 30,000 plants/ha. Crops were at maturity (harvesting period) at the time of the investigation.

In the field, cracked areas were considered as indicator of erosion. In fact, the farmers used the characteristics of the cracks to decide on the cropping on Vertisols. The wider and deeper the cracks, the less eroded is the soil and the more appropriate it is for post rainy season sorghum cultivation, because wider and deeper cracks are effective in absorbing rain water.

Sorghum characteristics, including plant height, length of the ear and diameter of the ear, were recorded at each observation point. A composite of five soil samples from the topsoil layer (0 – 5 cm) was collected at each observation point for determination of the organic matter content, particle size and pH (water).

(3) Rehabilitation of severely eroded soils: case study on Vertisols

(a) The principles of the experiment

Social and economic factors dictate that severely eroded soils, also called "Hardé" in the local dialect, be used for grazing, fire wood harvesting and sporadically for agriculture. Crop failure is frequent mainly because of slow permeability, infiltration and percolation. Recognizing the economic impracticality of deep subsoiling, simple surface practices were undertaken to examine their effects on the growth of rainfed sorghum (Sorghum S35). The design principles aimed at controlling erosion, conserving water by storage and improving infiltration.

Six crop characteristics were recorded: (1) percentage of plant stand 45 days after sowing, (2) percentage of plant stand 90 days after sowing, (3) root length 90 days after sowing, (4) plant height 90 days after sowing, (5) aerial biomass 90 days after sowing, and (6) grain production at harvesting (table 4.3). No chemicals were applied so that, crop development and behavior expressed only the effect of soil-moisture relationships.

Table 4.3 Field observations for rehabilitation of severely eroded Vertisols

Sorghum characteristics	Agricultural practices							
	Ridge system		Tied ridging		Microcatchment		Control plot	
	Obs/m²	Total	Obs/m²	Total	Obs/m²	Total	Obs/m²	Total
Plant stand (%) at day 45	1	200	1	200	1	200	1	200
Plant stand (%) at day 90	1	200	1	200	1	200	1	200
Root length (cm) at day 90	1	200	1	200	1	200	1	200
Plant height (cm) at day 90	1	200	1	200	1	200	1	200
Biomass (t/ha) at day 90	1	200	1	200	1	200	1	200
Grain yield (t/ha) at day 90	1	200	1	200	1	200	1	200
TOTAL	6	1200	6	1200	6	1200	6	1200

(b) Experiment lay out

Four types of agricultural practice were established on 10 m x 20 m plots, including the ridge-furrow system, tied ridging, microcatchment and control plot (figure 4.3). The experiment was a randomised block design without replication. The main characteristics are as follows:

- **Ridge-furrow system:** The soil surface was built up of 1 m-spaced parallel ridges of about 25 to 30 cm wide, with intervening furrows about 15 to 20 cm deep. The system was formed along the contour with a hand hoe, after ploughing by animal traction (a pair of cows). Surface runoff moves across the ridges to the furrows and then down the furrows. Sowing was done on the summit of the ridges at 1m distance interval. There were three seed-grains per seed-hole. A density of 30,000 plants/ha was obtained.
- **Tied ridging**: Tied ridging consisted of forming 1m-spaced ridges in two directions at right angles on the soil surface. In other words, the soil surface was built up of a series of rectangular depressions of about 15 to 20 cm deep. Surface runoff moves across the ridges and then stores in the surface depressions. Sowing was done at the ridge

intersections. There were three seed-grains per seed-hole. A density of 30,000 plants/ha was obtained.

- **Microcatchments**: Microcatchments were intermittent small semi-circular hoops or sections of terrace for individual plantings. Micro-depressions of about 40 to 50 cm diameter and about 10 cm deep were constructed at intervals along the contour and down the slope. A semi-circular bank 25 to 30 cm wide and 15 to 20 cm high was built on the lower side of the microcatchment, using soil excavated from the trench immediately above it. The space interval between two consecutive micro-depression lines was 1m. Micro-depressions on adjacent lines were in quincunx, such that any runoff water would be trapped in the micro-depression immediately below. Seed hole was made on the top of the bank. There were three seed-grains per seed-hole. A density of 30,000 plants/ha was obtained.
- **Control plot**: On the control plot, no practice was done except ploughing by animal traction (a pair of cows) along the contour. Seeds were sown at 1 m interval along the line. The distance interval between adjacent sowing lines was about 100 cm. There were three seed-grains per seed-hole. A density of 30,000 plants/ha was obtained. This practice is widely used on severely eroded soils of the Gawar area.

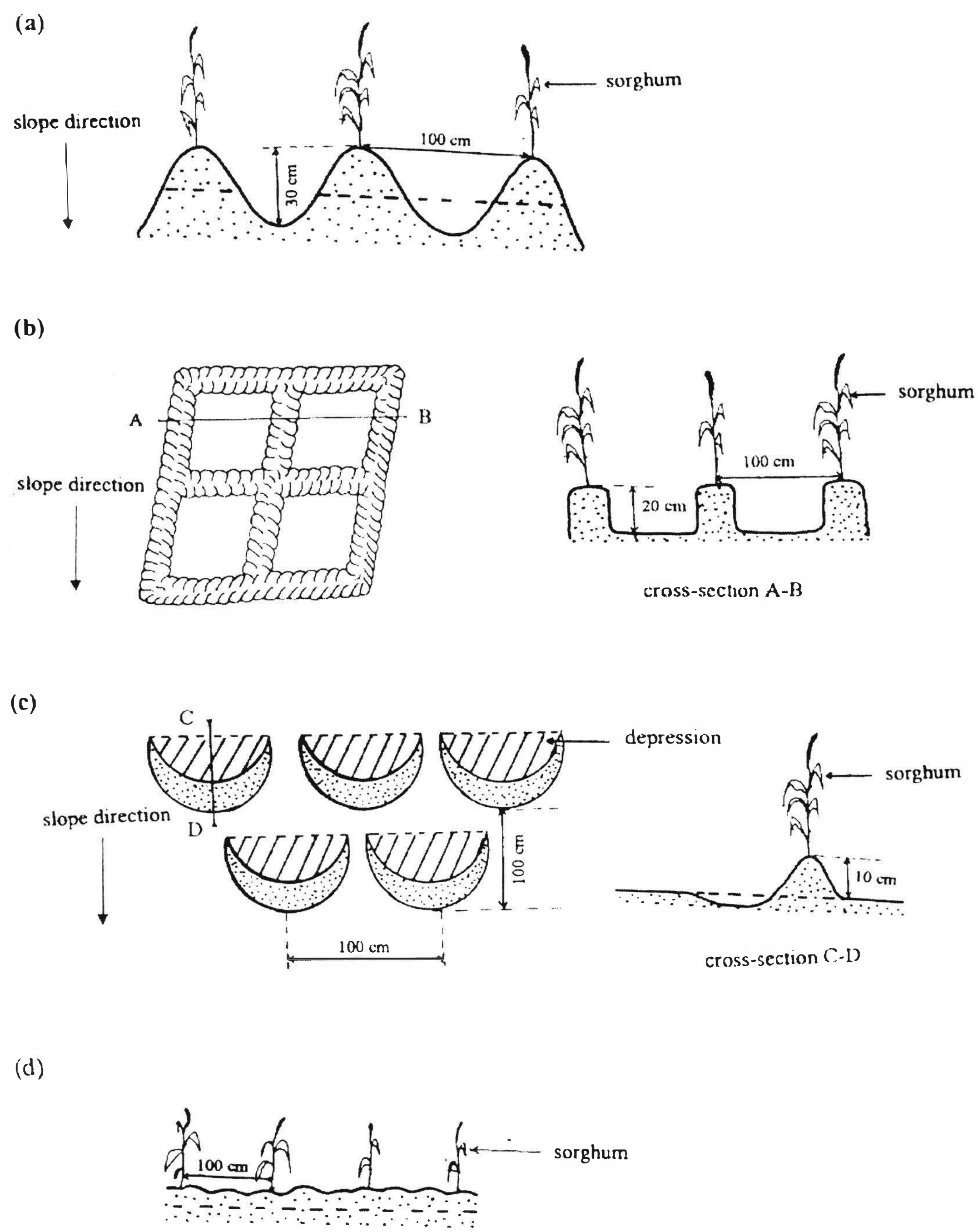


Figure 4.3 Agricultural practices (a) ridge-furrow system, (b) tied ridging, (c) microcatchment, and (d) control plot

4.1.3 Field investigations at micro-plot scale

(1) Rainfall simulation experiments

Spectacular damage by rill and gully erosion often hides the basic aspects of soil erosion and hydrology that occur at the level of very small plots. Erosion processes not discernible at the field or watershed level are yet fundamental to provide concepts and knowledge required for efficient development of research. Rainfall simulation experiments at micro-plot scale aimed at studying fundamentals of elemental interrill erosion processes. This study provided coherent and logical knowledge for the development of a local interrill soil erosion model, providing clear insight as to the relationships between soil properties and interrill erosion. Spatial and temporal variations of runoff, soil loss and resulting changes in the soil surface geometry, as affected by splash erosion and sheet wash, were investigated. Twenty-five sites representing the main regional soil units of the semiarid area of northern Cameroon, with different erosion classes, were subjected to artificial rainfall. Rain showers (three per plot) were simulated over one-square-meter plots at different intensities and durations using a field rainfall simulator (figure 4.4). Plots were bare and ploughed with a hand hoe. The method allowed the explicit consideration of factors determining both runoff and sediment concentration in detail.

(a) Equipment

The experimental equipment was a rainfall simulator developed by Asseline and Valentin (1978), suitable for studying erosion and runoff processes at the scale of one square meter. It is a pyramidal tower made of metallic tubes, easy enough to be carried by four men and that can be taken to pieces (figure 4.4). It produced rain showers with characteristics similar to natural rainfalls and allowed to model rainfall intensity, rainfall amount, rainfall duration, kinetic energy, and homogeneous distribution of rainfall drops over a square meter plot. The recorded runoff and soil loss reflected the integrated effect of all the processes that occurred during a rainshower (Asseline and Valentin, 1978).

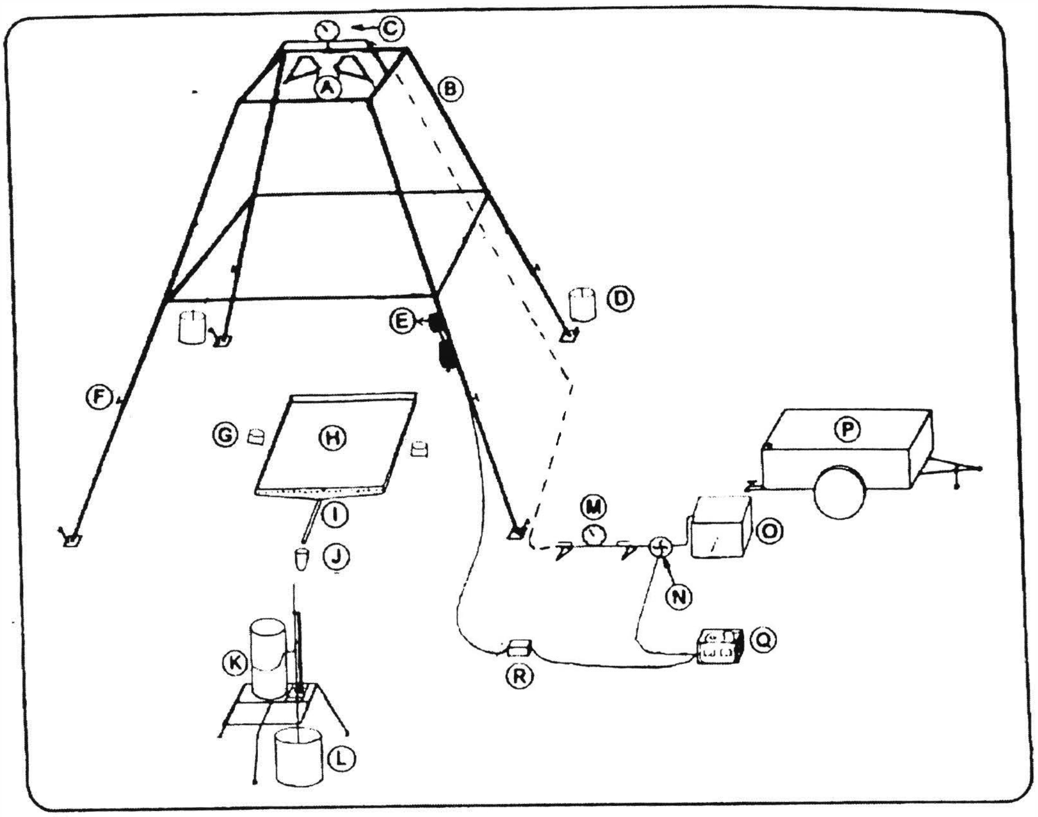


Figure 4.4 Field rainfall simulator (Asseline and Valentin, 1978)

A: nozzle for the production of the standard rain showers;
B: steel support for the nozzle, which is a pyramidal tower of 2 x 1.4m for the top, 4 x 2.8m for the base and 4.1m height; it also functions as wind shield in the field;
C: manometer (0-1 bar) for controlling water pressure (0.5 bar);
D: intermediate vase for recuperating and recycling water;
E: device for rainfall intensity setting;
F: adjustable supports according to the slope of the experimental plot;
G: splash cup;
H: steel frame of 1m x 1m for the test plot demarcation;
I: runoff conveyor tube to the recording system;
J: flask for sediment concentration sampling;
K: limnigraph for recording runoff characteristics;
L: runoff and sediment collector tank;
M: manometer (0-2 bars) for controlling the discharge and water pressure;
N: electrical pump;
O: intermediate water tank for supplying water to the sprayer;
P: mobile tank (1000 liters) for water storage and water supply;
Q: power generator (12 and 220 volts, 1500 watts);
R: battery for supplying power to the nozzle.

(b) General conditions of the experiments

The rainfall simulation experiments were conducted during the dry season (November - May). Three simulated showers of variable intensities and durations were performed on each plot. All selected sites were under similar conditions as follows:

- Water used for simulation of rain showers was collected from groundwater in wells dug in the river bed. That water was free of sediment, so that sediment contained in the runoff originated mainly from the experimental plot areas.
- The intensities and durations of showers were the same at all test plots.
- During simulated rainfall experiments, considerable amounts of sediment and water can be lost from the plot surface by splash (Bryan et al., 1989). These sediment and water losses were compensated by equivalent in-splashing amounts of sediment and water from a buffer zone around the target soil surface (the rainfall simulator sprayed the shower beyond the experimental plot, about a meter away from the external side of the plot). In this way, the effects of the border on the experiment were eliminated. The buffer zone also allowed to perform some physical tests to avoid any disturbance in the experimental area.
- The influence of the initial soil surface moisture was eliminated by the prewetting shower (first rain).
- Prior to the second rain, plots were ploughed with a hand hoe to obtain the initial soil surface roughness.
- The factor soil cover was standardized by the removal of vegetation and straw material from the soil surface.
- The slope length factor became irrelevant because of the small dimensions of the test plots. All experimental plots had 3% slope to facilitate runoff flowing.

The simulated rainfalls had the following characteristics (Asseline and Valentin, 1978):

- a rainfall event was a succession of 2 or 3 single rains with given intensity and duration;
- the first rain (or prewetting rain) was gentle, short, and had a uniform intensity;
- a shower was sprayed at a pressure of 0.4 bar to reflect natural conditions;
- the duration of a rainfall event did not exceed two hours to avoid extreme and rare rain conditions;

- the depth of a rainfall event was not higher than the daily rainfall of the annual frequency;
- the time interval between two showers was about 24 hours;
- rainfall intensity increased as the showers proceeded;
- the total rainfall sprayed over a plot did not exceed the mean annual rainfall.

Table 4.4 Characteristics of the simulated rain showers

Rain number	Time from previous rain	Intensity (mm/hr)	Duration (minutes)	Rainfall (mm)	Total rainfall (mm)
1	Three months	30	45	22.5	22.5
2	24 hours	30 40 60 30	15 30 30 15	7.5 20 30 7.5	65
3	24 hours	30 60 80 30	15 30 30 15	7.5 30 40 7.5	85
TOTAL RAINFALL (mm):					172.5

Equipment, procedures and methods were identical at all sites. Thus, the approach allowed elimination of the influence of all erosion factors, apart from the factor soil (soil properties). The purpose of this was to minimize as much as possible exogenous sources of variation that might influence the measurements.

(c) Study of surface runoff hydrograph parameters

- **Antecedent soil moisture content**

Antecedent soil moisture content was determined gravimetrically. Soil samples were taken before each rainfall storm, in the buffer zone around the experimental plot. The procedure consisted of removing samples by augering the upper 30 cm of the soil, at 10 cm depth intervals. Moist and dry weights were determined. The moist weight was determined by weighing soil samples as they were at the time of sampling (care was taken to avoid evaporation). The dry weight was obtained after drying the samples at a constant temperature (105 °C) in an oven for 24 hours. The mass wetness was obtained by dividing the weight loss from drying by the weight of the dried sample.

- **Depression storage**

Time to ponding was defined visually as free water accumulated on approximately 50% of the plot surface. Time-to runoff was taken as the first water drop of a continuous flow that entered the runoff tank. The time difference was the time allocated to depressions to fill up. The amount of water stored was calculated from the rainfall intensity at that time interval. This computation was done on the assumption that the infiltration process was negligible at that precise moment, because of the saturation of the soil surface. This method gave only the volume of water stored in depressions prior to runoff commencement.

- **Runoff**

The water table in the collector tank was registered by a recorder stylet which yielded a runoff hydrograph. To each constant rate of the elevation of water level for a given time corresponded an increasing linear segment on the hydrograph. That segment was the resultant of the vertical elevation representing incremental runoff depth, and a horizontal movement representing the time laps.

The discharge rate expressed in mm/h was calculated by $q = \frac{e}{t} * h$, where e is the incremental elevation of the water level (mm), t is the incremental time (min), and h is the hourly time.

Integration of the discharge rate over the rainfall duration allowed the calculation of the total runoff depth. The runoff coefficient expressed in percentage was calculated as the runoff depth relative to the rain depth.

Table 4.5 Field measurements of runoff

Rain No	**Total plots**	**Rate of measurement**	**Total measurements/plot**	**Total measurements/rain**
1	25	0	0	0
2	25	1	9	225
3	25	1	9	225
TOTAL..				450

(d) Study of erosion parameters

- **Splash erosion**

During the simulated rainfall experiments, two cups of 18 cm diameter and 15 cm high each were placed next to the experimental plot to allow splash sediment trapping. Samples of splash off material were taken every ten minutes throughout each simulated rain (table 4.6). The samples were filtered through a blotting paper of known dry weight to remove splashed off water. Then, samples were taken to an oven for drying. The weight of splashed material was determined for each time interval, from the weight difference between the weights of the blotting paper before filtering and after drying. All the sample results obtained during each rain shower and for each experimental plot were added to obtain the total splashed sediment.

Table 4.6 Field measurements of splash detachment

Rain No	Total plots	Rate of measurement	Total measurements/plot	Total measurements/rain
1	25	0	0	0
2	25	1	9	225
3	25	1	9	225
TOTAL...450				

- **Interrill erosion**

During each simulated rain shower and from the commencement of the runoff flow at the outlet of the experimental plot, samples of flow were taken every ten minutes in phials of 250 ml each throughout the rainfall (table 4.7). Each sample was filtered through a blotting paper of known dry weight. Blotting papers were taken to the laboratory, where they were dried in an oven and re-weighted after drying.

Sediment concentration was calculated from the weight difference of the blotting paper before filtering and after filtering and drying. Multiplying that concentration data (g/cm^3) by the discharge at the time when the volumetric sample was taken yielded a measurement of erosion rate for each sample. Integration of the concentration rate over the duration of a rain allowed the calculation of the total soil loss.

Table 4.7 Field measurements of sediment concentration and soil loss

Rain No	Total plots	Rate of measurement	Total measurements/plot	Total measurements/rain
1	25	0	0	0
2	25	1	9	225
3	25	1	9	225
TOTAL..450				

It happened that during the rainfall event, some coarse particles did not reach the collector tank but remained in the gutter. Because they were set out of the experiment, they were considered as eroded material. These particles were also collected and dried in an oven, and the weight was determined. The total amount of eroded sediment expressed in g/m^2 was calculated by adding the amount of suspended particles in the runoff water to the coarse particles remained in the gutter.

(e) Study of the soil surface behaviour

- **Soil surface roughness**

Soil surface roughness was investigated. The method consisted of measuring soil surface elevation points with a ruler, from a reference baseline downwards to the soil surface, along transects 5 cm apart, on 1x1m-plots. Measurements were taken after each of the two consecutive simulated rains (second rain and third rain). The initial microtopography was recorded just after ploughing with a hand hoe, following the first shower or prewetting rain (table 4.8). Geostatistics was applied to analyze the temporal and spatial variation of the elevation points as affected by splash and sheet wash, using variogram modeling and kriging interpolation. This allowed to distinguish between erosion and deposition areas within each experimental plot.

Table 4.8 Measurements of soil surface elevation points

Treatment	Total plots	Distance (cm)	Measurements/plot	Total
After ploughing	25	5	400	10000
After rain 2	25	5	400	10000
After rain 3	25	5	400	10000
TOTAL...30000				

- **Surface sealing**

Surface seal was visually studied and classified into four groups. The first group indicated the initial surface structure after the ploughing operation. The second one indicated stable surface structure with no apparent sealing and still intact aggregates after a simulated rain. The third group showed sealed surface covering less than 50% of the total of the experimental plot area. The last group indicated almost completely sealed surface where individual surface aggregates were no longer recognizable.

- **Aggregate stability**

A torvane apparatus with blades of 4 cm high and 2 cm wide was pressed 1cm deep into the undisturbed soil surface next to the test plot, before and after each rainfall simulation experiment. The pressure needed to rotate the blades through the soil was read on a movable scale of the torvane handle, after removing the instrument from the soil. The scale was moved back to zero and the next reading was made. Ten readings were made on the same plot and averaged (table 4.9).

Table 4 .9 Field measurements of soil surface resistance

Rain No	Total plots	Rate of measurement	Total measurements/plot	Total measurements/rain
1	25	0	0	0
2	25	1	2	50
3	25	1	2	50
TOTAL...100				

As a second method, the crumb test was used for the study of aggregate stability (table 4.10). A crumb of soil (about 2 to 3 cm of diameter) preserved at the natural water content was dropped into a beaker of water (100 ml). The tendency for clay particles to go into colloidal suspension was observed at 10 minutes of immersion, using the following interpretation guide:

- Grade (1): no reaction, the crumb may slake in a flat pile, but no sign of cloudy water caused by the colloids in suspension.
- Grade (2): slight reaction, bare hint of cloud in water at the surface of the crumb (if cloud is easily visible, grade 3 was used).
- Grade (3): moderate reaction, easily recognizable cloud of colloids in suspension, usually spreading out in thin streaks at the bottom of beaker.

- Grade (4): strong reaction, the colloidal cloud covers nearly the whole bottom of the beaker, usually in a very thin skin. In extreme cases, all the water in the beaker becomes cloudy.

Table 4.10 Field observation of soil surface behaviour

Investigation	Total rains	Total plots	Total observations
Crumb test	2	25	50
Crusting	2	25	50

4.1.4 Laboratory determinations

Soil samples taken from the genetic horizons of the twenty-five representative profiles were analyzed for routine soil properties: pH (H_2O), pH (KCl), particle size (five fractions), organic carbon, exchangeable basic cations, cation exchange capacity, nitrogen, phosphorus and free iron (table 4.11).

Composite soil samples of the topsoil layer collected for variability of the soil properties within map units and those taken from the topsoil layer for spatial distribution of erosion features were analyzed for pH (H_2O), particle size (five fractions) and organic matter content (table 4.11).

All the soil samples were sent to the soil laboratory of IRAD-Yaoundé (Cameroon). A summary of the laboratory determinations is presented in table 4.8. The description of the analytical procedures is presented in the annex.

Table 4.11 Soil sampling for laboratory analysis

Soil property	Technique	Samples per area of interest			Total
		Modal profiles	Soil variability	Erosion features	
pH (H_2O)	1:2.5 soil- H_2O mixture (potentiometer)	87	231	160	478
pH (KCl)	1:2.5 soil-KCl mixture (potentiometrically)	87	231	160	478
Particle size	Begheijin and Schylenborgh	87	231	160	478
Organic carbon	Oxidation (colorimetrically)	87	231	160	478
Nitrogen	Kjeldahl	87			87
Phosphorus	Bray and Kurtz	87			87
Free iron (Deb extractable)	Dithionite (colorimetrically)	87			87
Aluminum	Titration (colorimetrically)	87			87
Exchangeable acidity	Titration (colorimetrically)	87			87
Exchangeable basic cations	Blackmore	87			87
Cation exchange capacity	Dichloroisocyanurate	87			87

4.2 DATA INPUT

4.2.1 Database

(1) Soil database

Using the ILWIS package, a relational database was created to store, manipulate, retrieve and display the data and information generated by the input files from the source objects: field observations and measurements, and previous maps. The conceptual scheme was basically derived from the conceptual design developed by Zinck and Valenzuela (1990). Its logical content included geoforms, soil survey observations and measurements, soil map units, erodibility classes, erosion hazard classes, among others. For every entity, a primary key or identifier was selected to navigate throughout the system and intercommunicate among the different files.

The object-oriented approach of the ILWIS package allowed classification, generalization, aggregation and association of a set of objects. The EXCEL program provided a convenient user interface Standard Query Language (SQL) between the user and the database to create tables, insert data and operate data manipulations.

(2) Erosion parameter database

EXCEL and SYSTAT programs were used to store, manipulate and retrieve erosion and runoff data generated by the field erosion experiments.

4.2.2 Digitalization

All maps were converted into digital format by the method of digitizing, where all the features were recorded as a series of X- and Y- coordinates, that is as vector data. Vector data were then converted into raster data structure in which data were presented by gridcells to facilitate data manipulation.

4.3 DATA PROCESSING

4.3.1 Mapping at watershed scale

(1) The soil map

The variability and distribution of the soils were studied by means of conventional soil mapping, using the geopedologic approach and soil-landscape pattern analysis (Zinck, 1988). The research included interpretation of aerial photographs at 1:30,000, study of geologic maps at various scales, consideration of previous soil maps and field observations. A topographic map at 1:50,000 scale was used as base map. Soils were studied in the field in soil pits (100 cm deep), minipits (30 – 50 cm deep) and augerings (50 – 100 cm deep). Soil description was based on the FAO Guidelines for soil profile description (FAO, 1990). Munsell Color Charts (1975) were used for the colour identification. Soils were classified according to CPCS (1967), Soil Taxonomy (USDA, 1996) and FAO (FAO-WRB, 1998). Map units were classified at the level of erosion phases. The final map at the scale of 1:50,000 was produced by integration of the sample areas results and some check point results outside the sample areas.

(a) Levels of disaggregation of the geoforms

The disaggregation of the study area into geomorphic units was determined by the synopsis of the geoform classification system (Zinck, 1988). Each map unit was characterized progressively into four components including (1) landscape, (2) relief, (3) lithology, and (4) landform.

- **Landscape**

The landscape component was the first subdivision level of the area. The subdivision was based on morphometric criteria and the position vis-à-vis the surrounding sceneries. Generally speaking, the landscape unit was defined as any element of the land characterized by a distinctive gross topographic and surficial expression, internal geological structure and sufficiently conspicuous to be included in a physiographic description (Howard and Spock, 1940). The main feature was a repetition of similar relief types or an association of dissimilar relief types, for instance valley, plateau, mountain, etc. (Zinck, 1988).

- **The relief/molding**

The relief was determined by a given combination of topography and geologic structure (e.g. cuesta, horst, etc). Molding was determined by specific morphoclimatic conditions or morphogenetic processes (e.g. glacis, terrace, etc) (Zinck, 1988). The portion of land may consist of distinctive and repetitive patterns of the surface form.

- **Lithology/facies**

The lithology component emphasized the petrographic nature of hard rocks (e.g. gneiss, limestone, etc.) or the origine/nature of soft cover formations (e.g. lacustrine, alluvial, etc.) (Zinck, 1988).

- **Landform**

The landform was defined as a conspicuous basic geoform type, showing a unique combination of geometry, dynamics and history (Zinck, 1988). It was the basic unit of the mapping structure for it influenced the farm lay-out and land management, which consequently determined erosion hazard at farm level. In other words, a landform unit represented a geomorphic unit that incorporated processes and systems of close interactions between physical (topography), physicochemical (soil) and managerial (human practice) factors that regulate water movement and influence erosion.

(b) Types of soil map units

With respect to the aggregation of soils contained within each map unit, two types of map unit were identified, namely consociation type and association.

- **Consociation**

In a consociation, at least 50% of the soil belong to the taxonomic unit that provides the name of the map unit. Most of the remaining soils are similar to the named soil so that major interpretations are not significantly affected (Soil Survey Manual, 1996).

- **Association**

An association consists of two or more dissimilar soils occurring in a regularly repeating pattern, which cannot be separated at the mapping scale considered (Soil Survey Manual, 1996).

(c) Erosion classes

Variations of characteristics observed within a given soil type were attributed to the modifications caused by soil erosion. The main type of erosion was accelerated erosion caused by human activities (agriculture and livestock). Four main erosion classes were identified: (1) slightly eroded, (2) moderately eroded, (3) severely eroded, and (4) extremely eroded. The characterization of each erosion class was based on the criteria established by Rhoton et al. (1991), Kreznor et al. (1992), and Soil Survey Manual (1996). The farmer's opinion was also taken into consideration.

- **Slightly eroded soils**

The soils have lost some of the original A horizon. The average soil loss is less than 25 percent of the original A horizon. Throughout most of the area, the thickness of the surface layer is within the normal range of variability of the uneroded soil. Some scattered eroded spots may be modified appreciably in the area. Slightly eroded soils show few rills, accumulation of sediment at the base of the slope or in the depressions.

- **Moderately eroded soils**

On average, the soils have lost 25 to 75 percent of the original A horizon or the uppermost 20 cm if the original A horizon was less than 20 cm thick. The surface layer consists of a mixture of the A horizon and materials from below. Some areas may be smooth; shallow gullies and few deep ones may be present.

- **Severely eroded soils**

On average, the soils from this class have lost 75 percent or more of the original A horizon or the uppermost 20 cm if the original A horizon was less than 20 cm thick. Material from below the original A horizon is exposed at the surface and some or all of the deeper horizons have been eroded throughout most of the area. Diagnostic soil horizons have been removed. The original soil is no longer identifiable except in isolated spots. Some areas may be smooth. There is an intricate pattern of gullies.

- **Extremely eroded soils**

This class consists of areas with more than 75 percent of rock outcrop out of the total surface area (summits and steep slopes of mountains or hillands).

(2) The soil erodibility map

The input parameters used to determine the interrill erodibility classes of different soil units of the study area were assessed. A soil erodibility map was produced by extrapolating the soil erodibility results on the geopedological map used as base map, at a scale of 1:50,000.

(3) The slope map

The slope map was derived from a digital elevation model by the means of GIS techniques (ILWIS, 1998). Using neighbourhood algorithms, slope steepness was calculated. Four classes of slope steepness were considered: (1) level to nearly level (0 – 3%), (2) undulating (3 – 8%), (3) rolling (8 – 16%), and (4) hilly to very steep (> 16%).

(4) The erosion hazard map

To produce an erosion hazard map, three input data files were used: a soil file, an interrill erodibility file and a slope (or topographic) file. A topographic map at the scale of 1:50,000 was used as a base map.

(5) The land use planning map

A land use planning map for sustainable land management was produced considering soil conservation methods and suggesting appropriate land uses to eliminate or curb soil erosion in the study area. Manageable factors of soil erosion such as agricultural practices and land cover were studied. A land use planning map was obtained by overlaying the erosion hazard map and manageable factor maps, using GIS (ILWIS) facilities.

4.3.2 Mapping at plot scale

Geostatistics was applied to produce maps displaying the spatial variation of erosion features, using variogram modeling and interpolation through kriging.

4.3.3 Mapping at micro-plot scale

Geostatistics was applied to produce maps displaying the spatial distribution of erosion and deposition areas throughout the micro-plots after each simulated rain shower. Variogram modeling and interpolation through kriging were used.

4.4 DATA ANALYSIS AND INTERPRETATION

Data analysis was carried out using several approaches, including classical statistics, numerical classification and geostatistics.

4.4.1 Classical statistical procedures

(1) Quantitative descriptive statistics

Quantitative descriptive statistics were applied to sets of selected soil properties and erosion parameters to describe quantitatively the variations that occurred within and between variables. It allowed also to select the location of the modal profiles and the location of the rainfall simulation experiments. Statistical estimates, such as the arithmetic mean, range, standard deviation and coefficient of variation, were calculated to characterize the variations.

(2) Regression analysis

Regression analysis was applied to sets of selected soil properties and erosion parameters to evaluate the causal relationships between variables. The method allowed to evaluate dependent or criterion variables and independent predictor variables. In addition, the analysis was based on rational and physical principles (physically-based approach), because understanding the logic of the physical processes is the pre-requisite for successful statistical modeling (Casenave and Valentin, 1988; Mannaerts, 1992).

Soil characteristics or combinations of soil characteristics were related through regression analysis to estimate functional relationships between selected soil properties and slope length and between soil properties and interrill soil erodibility. A structural mathematical model was determined in the form $y = b + ax$, where y represents dependent variables, b is a constant, a is a regression coefficient (or slope) and x represents independent variables.

4.4.2 Abstraction method

Abstraction was used to provide a simpler picture of interpreting and understanding data sets. The dissection method was used to establish different classes by dividing the measured range of the variable values at certain critical points. The critical points were determined from trends in the field observations. Basically speaking, four concepts of abstraction were used, including classification, generalization, aggregation and association.

- Classification was used to group several objects in a common class. For instance, soils were grouped into soil classes.
- Generalization consisted of grouping several classes of objects with common properties and behaviour into a more general superclass. For instance, a soil map unit consisted of similar polypedons.
- Aggregation included the creation of new object classes by grouping different objects in such a way that the attribute of the new classes is a combination of the attributes of the constituents. For instance, high and very high soil erodibility classes were generalized into a high to very high soil erodibility class.
- Association was the form of abstraction whereby new object classes were the grouping of a set of objects of similar type into higher level objects which are not necessarily mutually exclusive. Due to scale limitation, the association method was used to determine some map units.

4.4.3 Ranking method

The ranking method allowed the weighting of objects to provide a rule to establish an inherent order or ranking like "first", "second", etc. The ranking method was used to order interrill soil erodibility values of different soils into ordinal values. It was also used for selecting land use options.

Three main land use options for soil conservation in the Gawar area were determined. The first option was the preservation and protection of not (or slightly) eroded soils against detrimental land management. The second option was related to the conservation of soils which show high levels of erodibility. The last one consisted of rehabilitation and restoration of soils which have been destroyed or damaged in the past. The cartographic modeling and displaying were carried out using GIS (ILWIS system) techniques.

4.4.4 Geostatistics

Soil erosion features, including incidental features such as crop performances, vary continuously in space. Neighbouring observation points tend to display similar values. As a consequence, property values at different sites cannot be regarded as independent (Webster and Oliver, 1990). The features may be homogeneous only over a certain region or range, but it is not obvious. In other words, samples close to an unsampled location being estimated are better estimators than samples farther away. Therefore, erosion features can be regarded as regionalized variables.

Geostatistical methods refer specifically to the application of the theory of regionalized variables. Because geostatistics provides better understanding of the spatial distribution of erosion features over a relief and allows efficient measure design for conservation planning, more attention is devoted in the following paragraphs.

(1) Semivariogram estimation

The semivariogram is a measure of the rate of change with distance for attributes that vary in space (regionalized variables). It determines the relationship between the distance separating nearby samples and amount of correlation present. For any two places, x and x+h, some distance apart (h), the semivariance $\gamma(h)$ as a function of the distance h for any regionalized variable Z(x) is defined as half the expectation of the squared differences of Z(x) and Z(x+h):

$$\gamma(h) = \frac{1}{2}\Sigma[Z(x) - Z(x+h)]^2$$

where Σ denotes the mathematical expectation.

When the variable Z is measured at several places in an area and there are n pairs separated by the distance h or lag, then the average semivariance at this lag is calculated from:

$$\hat{\gamma}(\mathrm{h}) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} (Zi - Zi + h)^{2}$$

In geostatistics, the semivariogram is used to characterize the random function Z(x), which implies the intrinsic hypothesis, that is:

- the mathematical expectation $\Sigma[Z(x)]$ exists and does not depend on location x

  $\Sigma[Z(x)] = m, \forall(x);$
- for all distance (h) or lag between two locations, the increment $\Sigma[Z(x) - Z(x+h)]$ has a finite variance which does not depend on x,

  $\frac{1}{2}\mathrm{var}[\ Z(x+h) + Z(x)] = \frac{1}{2}\Sigma[\ Z(x+h) + Z(x)]^2 = \gamma(h), \forall(x).$

The lag of the experimental semivariogram is confined to one-half the extreme distance in the sampling domain for the direction to analyze. This allows to include the central point in the analysis (Journel and Huijbregts, 1978).

Local trends may occur in some areas so that the value of the variable is no longer constant: it changes with position. The intrinsic hypothesis is no longer valid, because the expected value is a function of the position:

$\Sigma[Z(x)] = U(x)$

The quantity U(x) representing the trend is known as the drift in regionalized variable theory. In these circumstances, proper semivariogram estimation practices require the removal of the trend. There are many ways to eliminate the trend. The method used in the present research consisted of subtracting an analytical function through regression analysis. Residuals were computed to remove outliners or trend in the data set, then treated as new data set from which variogram parameters were determined (Olea, 1994).

The variogram graph consists of three basic concepts; these are continuity, zone of influence and anysotropy.

(a) Continuity

Continuity refers to the smoothness of the transition between very closely spaced samples. It is measured by the rate at which $\gamma(h)$ grows near the origin of the variogram graph. By definition $\gamma(0)$ is zero. In practice, a variance exists at zero distance. This phenomenon is called nugget effect. The higher the nugget, the higher the variation at short distance. A variogram may be totally devoid of any spatial continuity, meaning that variability is essentially constant for all distances. This implies that the data are independent. The situation is termed pure nugget effect.

(b) Zone of influence

The zone of influence refers to a certain distance (or range) within which similarity between samples is noted. Beyond that zone, the graph flattens and data are said to be independent. The height at which this plateau is reached is called the sill.

(c) Anisotropy

Erosion features vary in two lateral dimensions in a plane, the direction along the contour and that along the slope. The variations in the two directions are obviously different. The variation of erosion features tends to be more substantial along the slope than along the contour, which signals anisotropy. For instance, rill characteristics vary more gradually parallel to the hillslope, from the top down to the slope bottom, than at right angles (contours) to it. Rills are narrow and shallow upslope, but they tend to be wide and deep downslope. As a consequence, the study of the spatial variability of erosion features at the plot level focused only on the variation along the slope.

At micro-plot scale, geostatistics was applied to a set of 256 values of the soil surface elevation points, measured with a ruler, from a reference baseline downwards to the soil surface, along transects 5 cm apart, on 1 x 1 m-plots. Measurements were taken just after ploughing with a hand hoe, following the first shower or prewetting rain, and after each simulated rain subsequent to ploughing (second rain and third rain).

At plot scale, geostatistics was applied to a set of 80 values for each selected soil property measured on composite soil samples, collected from the topsoil layer (0 to 5 cm), using a systematic sampling technique. Composites of five soil samples were taken in a grid-form at 8 m interval between observations, on two plots of 40 m x 104 m each, on moderately eroded Lixisols and moderately eroded Vertisols. Semivariograms for data sets of the selected erosion features, including the thickness of the topsoil layer, particle size, organic matter content, among others, were established. The number of observation points (80) was a limitation, compared to the minimum number of 100 observation points required per sample area (Webster and Oliver, 1990; Webster and Oliver, 1992). Nevertheless, this limitation did not affect substantially the spatial structure of the variogram. Similarly, Sterk and Stein (1997) reported a full characterization of the spatial variability with a data set of less than 100 observation points per sample area.

(2) Fitting the models

A variogram model is positive definite, which ensures that interpolation equations constructed with this model have one, and only one, stable solution. Models are preferably fitted using a statistically based computer program, with semivariance as the dependent variable and lag as the predictor. Variogram models with sills and plateaus are called transitive models, including the spherical model, exponential model and gaussian model. Variogram models without sills include the pure nugget effect model and linear model. The spherical, linear and gaussian models applied to the present data sets (figure 4.5). The fitting of the was done with the help of a computer software (Variowin program).

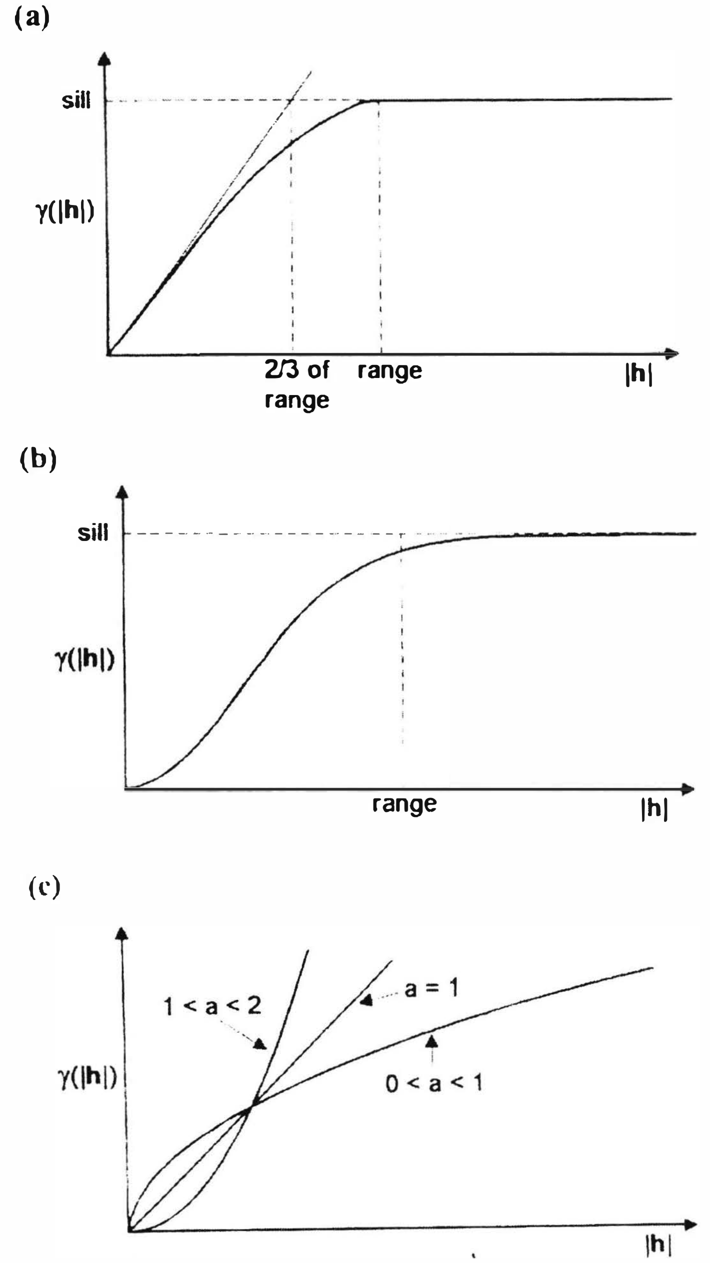


Figure 2.5 Variogram models (a) spherical model, (b) Gaussian model, and (c) linear model

(a) Spherical model

The spherical model is a bounded model in which the semivariance increases linearly from zero with increasing lag, until it reaches its sill and therefore remains constant. Its formula is:

$$\gamma(h) = c\{\frac{3h}{2a} - \frac{1}{2}(\frac{h}{a})^3\} \quad \text{for } h \leq a$$

$$\gamma(h) = c \qquad\qquad\qquad\qquad \text{for } h > a$$

where c is the sill and a the range.

(b) Gaussian model

The Gaussian model reveals extremely continuous phenomena. It has a parabolic form near the origin. The sill is approached assymptotically. Its equation is given by:

$\gamma(h) = c\mathrm{Gauss}_a(h)$

where c is the sill and a the range.

(c) Linear model

The linear model does not reach a sill but increases with the magnitude of the lag. The main advantage of the linear model is its simplicity. Its equation is given by:

$\gamma(h) = wh$

where w is the slope.

(3) Interpolation using kriging technique

Whereas variograms provide the assessment of the spatial correlation structure present, the technique of kriging provides the tool that enables the geostatistics to fully use the information derived from the variograms. Spatial classification of the erosion features in the area of interest was done by interpolation, using the kriging method. It is a method of weighted averaging of the observed values of a given property within a neighbourhood. The method provides statistically sound estimates and can be used to plan sampling in a rational way (Webster and Oliver, 1990).

The display of the spatial distribution of the variables on maps was performed by a computer program (Surfer), which showed spatial distribution classes as layered shading or colouring.

4.5 JUSTIFICATION OF THE METHODS AND TECHNIQUES

The desirable approach to investigate the inherent susceptibility of soils to erosion (or soil erodibility), namely the K factor in the Universal Soil Loss Equation (USLE), is based on actual measurements of soil loss from selected natural sites over long periods of time. Such an approach allows to take into account varieties of rainstorms, antecedent soil moisture and surface conditions. It also requires that valuable land remain in fallow for many years (El-Swaify and Dangler, 1976). In the meantime, erosion would have reached severe states before suitable models are developed. As a consequence, the farmers would face expensive restoration problems, instead of simple problems of soil conservation.

The advantage of using a rainfall simulator is that rain characteristics such as intensity, duration and amount can be controlled. The major advantages of a rainfall simulator are fourfold: it is more rapid, more efficient, more controlled and more adaptable than the natural rainfall. One can make measurements and observations during simulated storms that are difficult or impossible during natural storms (Meyer, 1988). Furthermore, investigating the influence of soil properties on hydrologic and erosion phenomena is better done when using a rainfall simulator. Conclusive results from field plots, that rely on natural rainfall, require many years of measurements, while simulated rainshowers provide in short time data useful for erosion research (El-Swaify and Dangler, 1976).

The importance of using small plots was their utility in studying the basic aspects of soil erosion and hydrology in detail. For practical reasons, a square meter plot is a useful scale and is also the usual scale for measurements of runoff under rainfall simulation experiments (Valentin, 1988). Small plots provide basic concepts and knowledge required for efficient developmental research. Phenomena not discernible at the field or watershed levels, such as splash erosion, runoff generation, crust formation, aggregate stability or ponding time, can be studied with great accuracy. Another advantage of using small plots was that many replications were done at lower costs. In fact, the plot size determines to a large extent the types of erosion processes that occur and the intensity at which they operate. Therefore, it is clear that at small plots (a square meter) the sediment sources (splash - interrill) as well as the amount of sediment output can be determined. The erodibility in these conditions is then classified as interrill soil erodibility.

A quantitative measure of soil erodibility as determined from micro-plots in laboratory conditions may not be identical to that obtained on the field plots, because the infiltration characteristics of a shallow layer of soil are not similar to those of a deep profile from the field (Lal, 1981). The justification for using bare and ploughed plots is that in semiarid zones substantial soil losses from cultivated fields occur at the beginning of the rainy season because of the absence of plant cover. Also, apart from rainfall characteristics, experiments were conducted in situ (no manmade soil, no disturbance), therefore the amounts of runoff and soil loss reflected the reality of the hydrological and erosion processes in natural conditions.

The reason for using a process-based method is that the trend in erosion prediction in the USA, Australia and Europe is toward the development of process-based simulation models. The emphasis in erosion research on strictly empirically based models such as the USLE is declining (Nearring et al., 1990). Therefore, it might be worthwhile to soil erosion scientists, from developing countries in general and from Cameroon in particular, to cope with the new trend for their contribution to effective erosion research methods.

For many years already, research workers have looked for soil properties which give a significant correlation with the soil erodibility factor, using predictive equations that contain, as independant variables, easily measurable basic soil parameters that are strongly correlated with erodibility. The great advantage of using soil properties, in comparison with direct measurement in the field, is speed and simplicity for soil erodibility assessment (Verhaegen, 1984).

CHAPTER 5

SOIL TYPES AND EROSION CLASSES

5.1 INTRODUCTION

Soil map units are based on differences in soil types, each of which having a unique set of interrelated characteristics. A soil unit needs to be uniform for reliable data aggregation and determination of the soil erodibility. The properties of a given soil type allow to predict the erosional behaviour of that soil and serve as basis for planning soil and water conservation strategies. Soil properties may change because of erosion, leading to spatial and temporal variability of the soil erodibility within a given soil type. In other words, it is expected that (1) variations between erosion classes change with erosion severity, and (2) variations within erosion classes are small compared to variations within a soil type as a whole. Many erosion studies restrict the erodibility concept to uneroded soils because of their high potential for agriculture. The erodibility concept can also apply to eroded soils where information on the erosional behaviour is important for soil restoration and rehabilitation or for non-agricultural uses.

In the Gawar area, pressure on the land over centuries with improper management practices has caused erosion, so that uneroded soils do not exist anymore as reference soils with original characteristics. In addition, the extension rates of erosion cannot be precisely assessed because aerial photographs showing the erosion status of the area at different periods are not available. To characterize the present state of the soils, the variability and distribution of the soils were studied by means of conventional soil mapping, using the geopedologic approach and soil-landscape pattern analysis. The comparison between erosion classes within a given soil is emphasized.

5.2 SOIL TYPES AND THEIR PROPERTIES AS AFFECTED BY EROSION

Five main soil types are found in the Gawar area: Alfisols, Vertisols, Inceptisols, Entisols, and Planosols. Erosion causes modifications that affect the topsoil characteristics, inducing spatial variations of soil properties within the soil types. The erosion classes of the main soil types are presented in figure 5.1 and table 5.1. The morphological, physical and chemical properties of the soil types, with emphasis on the changes caused by erosion, are described based on field investigations, laboratory analysis and previous works by Segalen (1962), Sieffermann (1963), Pontanier and Kotto-Samé (1982), and Brabant and Gavaud (1985). A comparison between soil characteristics is made to highlight the differential state of erosion affecting the major soil types. Three erosion classes were identified: (1) slightly eroded, (2) moderately eroded, and (3) severely eroded.

5.2.1 Alfisols

Alfisols are mostly reddish brown (2.5YR 4/4, dry) or yellowish brown (10YR 5/6, dry) and show translocation of clay from the surface horizons to the subsoil horizons (argillic horizon). However, many soil properties change according to erosion severity. Less eroded soils are on nearly level to gently sloping mesas in the plateau and on the treads of the glacis-terraces in the plain, whereas more eroded soils are on convex ridge summits and convex backslopes of the "half-orange" hills in the peneplain, and on the sloping risers of the glacis-terraces in the plain. Slope ranges from 0 to 3% on less eroded soils and from 2 to 8% on more eroded soils.

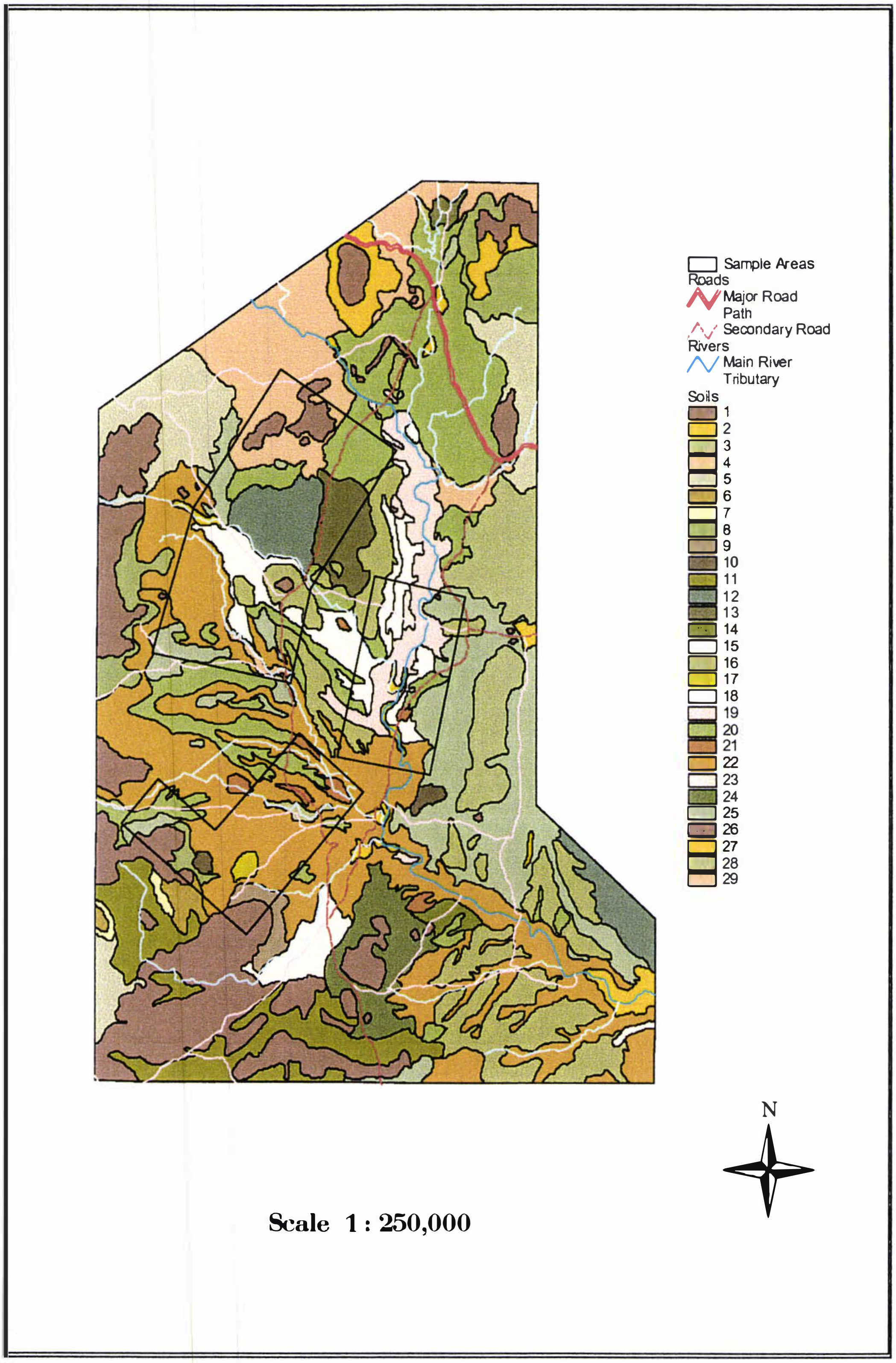


Figure 5.1 Geopedologic map of the Gawar area

Table 5.1 Legend of the geopedologic map (figure 5.1)

Landscape	Relief/Molding	Altitude (m)	Lithology	Landform	Map unit type	Slope (%)	Soil classification			Erosion class	Area (ha)	MU
							CPCS (1967)	USDA (1996)	FAO (1998)			
Mountain	Ridges	700 - 1060	Granite, migmatite, anatexite, quartzite, basalt	Slope-facet complex	Association	15 - 60	Peu évolués d'érosion (*)	Lithic Ustorthents (*)	Lithic Leptosols Rock outcrops	Excessive	10230	1
				Footslope	Consociation	12 - 20	Fersiallitiques	Lithic Ustropepts	Eutric Cambisols	Slight	1215	2
Hilland	Ridges	700 - 965	Granite	Slope-facet complex	Association	33 - 43	Peu évolués d'érosion (*)	Lithic Ustorthents (*)	Lithic Leptosols Rock outcrops	Excessive	3345	3
Plateau	Hills in "half-orange"	700 - 900	Granite, migmatite, anatexite	Slope-facet complex	Association	8 - 9	Fersiallitiques Peu évolués d'érosion	Lithic Ustropepts Lithic Ustorthents	Eutric Cambisols Lithic Leptosols	Slight	5620	4
					Association	19 - 23	Peu évolués d'érosion (*)	Lithic Ustorthents (*)	Lithic Leptosols Rock outcrops	Severe	3659	5
	Mesas	800 - 850	Gneiss, embrechite	Tread	Consociation	0 - 1	Ferrugineux	Typic Haplustalfs	Haplic Lixisols	Slight	386	6
	Escarpments	600 - 800	Gneiss, embrechite (pediment)	Scarp-talus complex		24 - 40	Fersiallitiques Peu évolués d'érosion	Lithic Ustropepts Lithic Ustorthents	Eutric Cambisols Lithic Leptosols	Severe	182	7
Piedmont	High glacis	580 - 600	Colluvium	Erosional glacis	Consociation	11 - 15	Peu évolués d'érosion	Lithic Ustorthents	Lithic Leptosols	Severe	2261	8
	Low glacis	560 - 580	Colluvium	Erosional glacis	Consociation	5 - 8	Ferrugineux	Kanhaplic Haplustalfs	Haplic Lixisols	Moderate	458	9
	Hills	700 - 900	Granite, anatexite	Slope-facet complex	Association	20 - 40	Peu évolués d'érosion (*)	Lithic Ustorthents (*)	Lithic Leptosols Rock outcrops	Excessive	212	10
Peneplain	Hills in "half-orange"	600 - 650	Granite, migmatite, anatexite, gneiss	Slope-facet complex	Association	4 - 6	Ferrugineux Fersiallitiques vertiques	Kanhaplic Haplustalfs Vertic Ustropepts	Haplic Lixisols Vertic Cambisols	Moderate	3871	11
				Slope-facet complex	Association	4 - 8	Peu évolués d'érosion Fersiallitiques	Lithic Ustorthents Typic Ustropepts	Lithic Leptosols Haplic Cambisols	Severe	2256	12

(*): Rock outcrops

Table 5.1 (continuation)

Landscape	Relief/Molding	Altitude (m)	Lithology	Landform	Map unit type	Slope (%)	Soil classification			Erosion class	Area (ha)	MU
							CPCS (1967)	USDA (1996)	FAO (1998)			
Plain	High erosion glacis	590 - 605	Migmatite, quartzite embrechite	Tread-riser complex	Consociation	2 - 6	Ferrugineux	Kanhaplic Haplustalfs	Haplic Lixisols	Moderate	1186	13
					Association	3 - 8	Fersiallitiques vertiques Ferrugineux Halomorphes	Vertic Ustropepts Kanhaplic Haplustalfs Aridic Haplustalfs	Vertic Cambisols Chromic Lixisols Haplic Planosols	Severe	299	14
	Middle erosion glacis	560 - 590	Gneiss, quartzite	Tread	Consociation	0 - 1	Ferrugineux	Typic Haplustalfs	Haplic Lixisols	Slight	1919	15
			Embrechite	Tread	Consociation	0 - 1	Vertisols	Typic Haplusterts	Eutric Vertisols	Slight	6949	16
				Riser	Consociation	1 - 2	Fersiallitiques vertiques	Vertic Ustropepts	Vertic Cambisols	Slight	132	17
	Low erosion glacis	510 - 560	Gneiss, quartzite	Tread	Consociation	2 - 4	Ferrugineux	Typic Haplustalfs	Haplic Lixisols	Moderate	1825	18
				Riser	Consociation	2 - 6	Ferrugineux	Typic Haplustalfs	Chromic Lixisols	Severe	2345	19
			Embrechite	Tread	Consociation	2 - 4	Vertisols	Typic Haplusterts	Haplic Vertisols	Moderate	10260	20
				Riser	Consociation	3 - 5	Vertisols	Typic Haplusterts	Haplic Vertisols	Severe	460	21
					Consociation	3 - 10	Fersiallitiques vertiques	Vertic Ustropepts	Vertic Cambisols	Moderate	16569	22
			Gneiss, migmatite	Tread	Consociation	2 - 3	Halomorphes	Aridic Haplustalfs	Haplic Planosols	Slight	74	23
				Riser	Consociation	2 - 13	Halomorphes	Aridic Haplustalfs	Haplic Planosols	Moderate	2071	24
					Consociation	2 - 5	Halomorphes	Aridic Haplustalfs	Haplic Planosols	Severe	7851	25
	Inselberg	600 - 800	Granite, quarzite, basalt	Slope-facet complex	Association	40 - 60	Peu évolués d'érosion (*)	Lithic Ustorthents (*)	Lithic Leptosols (*)	Excessive	418	26
Valley	Floodplain	510 - 580	Recent alluvium	Tread	Consociation	0 - 1	Peu évolués d'apport	Udic Ustifluvents	Haplic Fluvisols	Slight	1147	27
					Consociation	0 - 1	Peu évolués d'apport	Udic Ustifluvents	Haplic Fluvisols	Moderate	144	28
	Terrace	550 - 580	Ancient alluvium	Tread	Consociation	3 - 4	Peu évolués d'apport	Typic Ustropepts	Fluvic Cambisols	Moderate	579	29

(*): Rock outcrops

(1) Morphological properties

Substantial changes in the properties occur in the topsoil layers. The thickness decreases, the colour is lighter and the structure is coarser or massive, as the severity of erosion increases. For instance, on slightly eroded Alfisols, surface horizons are dark brown (10YR 3/3, dry) to brown (7.5YR 5/4, dry), 15 to 28 cm thick, with massive primary structure breaking into single grains. On severely eroded Alfisols, surface horizons are yellowish brown (10YR 5/4, dry) to red (2.5YR 4/8, dry), 3 to 5 cm thick, with subangular blocky or massive structure (table 5.2). Surface horizons of less eroded soils absorb water more readily than those of more eroded soils.

Table 5.2 Morphological properties of the erosion classes on Alfisols

Morphological properties	Erosion classes		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Thickness (cm):			
-surface horizons	15 – 28	10 – 14	3 – 5
-solum	100 – 150	100 – 125	75 – 100
Colour (dry):			
-surface horizons	dark brown to brown	pale brown to reddish brown	yellowish brown to red
-subsurface horizons	brown to yellowish brown	yellowish brown to red	brown to red
Structure:			
-surface horizons	massive to single-grained	massive to subangular blocky	subangular blocky or massive
-subsurface horizons	subangular blocky	subangular blocky or massive	massive

(2) Physical properties

Physical properties in the topsoil layers change according to erosion classes. The texture is finer, the bulk density increases and the coarse particle contents increase at various percentages, with increasing erosion severity. For instance, on slightly eroded Alfisols, clay content varies in the surface horizons from 5 to 7%, with loamy sand texture. The bulk density varies from 1.3 to 1.5 Mg m^{-3}. On severely eroded Alfisols, clay content varies in the surface horizons between 17 and 30%, with sandy clay loam texture. Nodules of iron and manganese are common. The bulk density varies from 1.6 to 1.7 Mg m^{-3} (table 5.3).

Table 5.3 Physical properties of the erosion classes on Alfisols

Physical properties	Erosion classes		
	Slightly eroded	Moderately eroded	Severely eroded
Clay content (%):			
-surface horizons	5 – 7	7 – 15	17 – 30
-subsurface horizons	12 – 27	31 – 42	26 – 34
Silt content (%):			
-surface horizons	18 – 21	12 – 23	14 – 25
-subsurface horizons	21 – 25	10 – 22	13 – 24
Sand content (%):			
-surface horizons	70 – 74	65 – 85	52 – 56
-subsurface horizons	63 – 74	43 – 76	48 – 54
Textural class (USDA):			
-surface horizons	loamy sand	sandy loam	sandy clay loam
-subsurface horizons	sandy loam	sandy clay loam to sandy clay	sandy clay loam to clay loam
Coarse particles (%):			
-surface horizons	2 – 4	5 – 36	8 – 25
-subsurface horizons	5 – 10	11 – 62	10 – 30
Bulk density (Mg m^{-3}):			
0 to 10 cm	1.3 – 1.5	1.5 – 1.6	1.6 – 1.7
10 to 20 cm	1.5 – 1.6	1.6 – 1.7	1.6 – 1.7
20 to 30 cm	1.4 – 1.5	1.5 – 1.6	1.6 – 1.7

(3) Chemical properties

Chemical properties change within and between soil profiles of the erosion classes. Drastic changes occur in the topsoil layers. Properties, such as exchangeable basic cations, cation exchange capacity and pH, decrease with increasing erosion severity. Free iron contents increase whereas organic matter contents fluctuate, with increasing erosion severity.

For instance, on slightly eroded Alfisols, organic matter contents vary from 0.5 to 1%, free iron contents vary from 1 to 1.3%, sum of exchangeable basic cations varies from 11.6 to 30.4 cmol (+) kg^{-1} of soil, cation exchange capacity oscillates between 10 and 31 cmol (+) kg^{-1} of soil, and the pH values range from 6.6 to 6.8. But on severely eroded Alfisols, organic matter contents vary from 0.1 to 1%, free iron contents vary from 1.5 to 2.6%, sum of exchangeable basic cations varies from 8.1 to 9 cmol (+) kg^{-1} of soil, cation exchange capacity varies from 7.5 to 11.7 cmol (+) kg^{-1} of soil, and the pH values range from 5.8 to 6.5 (table 5.4). The increase of the exchangeable basic cations, cation exchange capacity and pH with soil depth can be attributed to the parent materials. In fact, as the surface horizons are eroded the depth to the C horizon decreases, which affects the properties of the topsoil layers.

On average, variations in soil properties with erosion severity can be explained by selective erosion (figure 5.2). In fact, at the intermediate stage of erosion (on moderately eroded Alfisols), the sand and gravel contents increase due to selective removal of clay. Organic matter contents and nutrients associated with the clay fraction decrease. This results in loss of soil cohesion, which enhances erosion of the sand fraction, especially during heavy rainfall events. The removal of the sandy topsoil layers is accompanied by the exposure of compact and clayey subsoil layers at the latter stage of erosion (on severely eroded Alfisols). Baver et al. (1972), Frye et al. (1982), Larson et al. (1985) and Seiny (1990) report similar results.

Table 5.4 Chemical properties of the erosion classes on Alfisols

Chemical properties	**Erosion classes**		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Organic matter content (%):			
-surface horizons	0.5 – 1	0.1 – 0.5	0.1 – 1
-subsurface horizons	0.2 – 0.3	0.2 – 0.3	0.2 – 0.5
Carbon/nitrogen ratio:			
-surface horizons	5.3 – 8	1.8 – 12.7	0.7 – 0.8
-subsurface horizons	2 – 4	2.4 – 14.1	2.2 – 8.2
P_2O_5 Bray II (cmol kg^{-1} of soil):			
-surface horizons	26 – 31	2 – 4	1 – 4
-subsurface horizons	10 – 33	1 – 3	2 – 5
Fe_2O_3 free iron (%):			
-surface horizons	1 – 1.3	0.5 – 3.1	1.5 – 2.6
-subsurface horizons	1.7 – 2.2	1.8 – 3.2	1.5 – 2.6
Exchangeable basic cations (cmol (+) kg^{-1}):			
-surface horizons	11.6 – 30.4	2.2 – 29	8.1 – 9
-subsurface horizons	12.6 – 16.3	4.8 – 22.6	8.5 – 12.7
Cation exchange capacity (cmol (+) kg^{-1}):			
-surface horizons	10 – 31	2 – 30	7.5 – 11.7
-subsurface horizons	10.9 – 27.9	4 – 25.9	8.5 – 25.3
pH (1:2.5 soil/water suspension):			
-surface horizons	6.6 – 6.8	6.3 – 7.3	5.8 – 6.5
-subsurface horizons	6.2 – 6.4	6.2 – 8.1	5.7 – 8.7

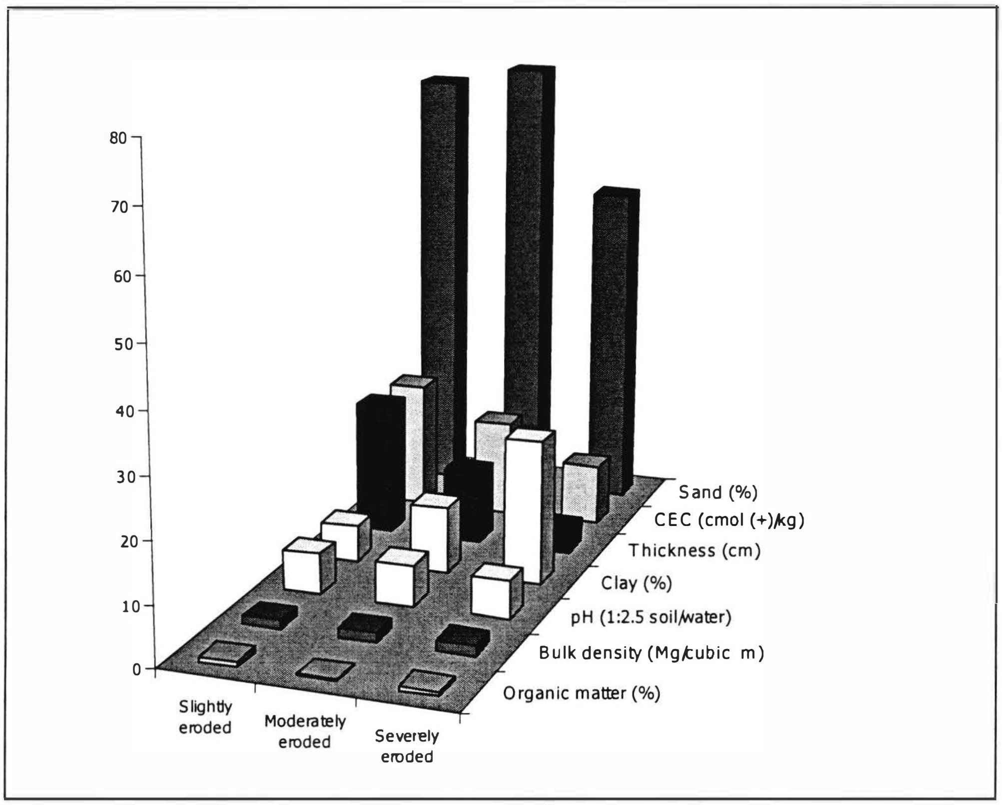


Figure 5.2 Average values of selected topsoil properties within erosion classes on Alfisols

5.2.2 Vertisols

Vertisols are formed on fine textured materials. In most years, they have large and deep cracks during the dry season. The dominant clay mineral is montmorillonite. Nevertheless, the properties of the Vertisols vary according to erosion severity. Three erosion classes were identified: (1) slightly eroded, (2) moderately eroded, and (3) severely eroded. Typically, less eroded Vertisols are on nearly level to gently sloping treads (0 to 3% slope), whereas more eroded Vertisols are on undulating treads and risers (2 to 4% slope) of the glacis-terraces, in the plain.

(1) Morphological properties

Substantial changes in the properties occur in the topsoil layers of the erosion classes. The thickness decreases, the colour is lighter, the structure is coarser and the cracked area at the soil surface decreases, with increasing erosion severity. For instance, on slightly eroded

Vertisols, the surface layers are dark gray (5Y 4/1, dry), 10 to 50 cm thick, with medium prismatic structure. Cracks are 2 to 3 cm wide and 50 to 100 cm deep from January to June. Cracked areas are more than 5% at the soil surface. On severely eroded Vertisols, the surface horizons are brownish gray (2.5Y 6/2, dry), 2 to 20 cm thick, with prismatic or subangular blocky structure. Cracks are 0.5 to 1 cm wide and 30 to 55 cm deep from January to June. Cracked areas are less than 2% at the soil surface (table 5.5).

Table 5.5 Morphological properties of the erosion classes on Vertisols

Morphological properties	Erosion classes		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Thickness (cm):			
-surface horizons	10 – 50	4 – 35	2 – 20
-solum	> 150	100 – 150	< 100
Colour (dry):			
-surface horizons	dark gray	brownish gray to grayish brown	brown gray
-subsurface horizons	dark gray	grayish brown	grayish brown or brown gray
Structure:			
-surface horizons	medium prismatic	prismatic, subangular blocky or platy	subangular blocky
-subsurface horizons	coarse prismatic	subangular blocky or massive	prismatic or massive
Crack characteristics:			
-width (cm)	2 – 3	1 – 2	0.5 – 1
-depth (cm)	50 – 100	35 – 60	30 – 55
-area (%) at soil surface	> 5	2 - 5	< 2

(2) Physical properties

Physical soil properties in the topsoil layers change according to erosion classes. The texture is finer, the coarse particle contents increase and the bulk density increases, with increasing erosion severity. For instance, on slightly eroded Vertisols, clay content in the surface horizons varies from 29 to 37%, with sandy clay loam to clay loam texture, and the bulk density is 1.3 Mg m^{-3}. On severely eroded soils, clay content in the surface horizons varies between 29 and 40%, with sandy clay loam to clay texture and abundant calcareous nodules regularly distributed. The bulk density varies from 1.4 to 1.5 Mg m^{-3} (table 5.6).

Table 5.6 Physical properties of the erosion classes on Vertisols

Physical properties	Erosion classes		
	Slightly eroded	Moderately eroded	Severely eroded
Clay content (%):			
-surface horizons	29 – 37	24 – 32	29 – 40
-subsurface horizons	39 – 41	33 – 41	33 – 40
Silt content (%):			
-surface horizons	21 – 28	13 – 20	26 – 27
-subsurface horizons	21 – 23	16 – 26	16 – 26
Sand content (%):			
-surface horizons	45 – 54	50 – 62	34 – 42
-subsurface horizons	40 – 45	41 – 58	36 – 51
Textural class (USDA):			
-surface horizons	sandy clay loam to clay loam	sandy clay loam	sandy clay loam to clay
-subsurface horizons	clay loam	sandy clay loam to clay	sandy clay to clay
Coarse particles (%):			
-surface horizons	5 – 10	5 – 20	10 – 20
-subsurface horizons	10 – 20	15 – 35	25 – 35
Bulk density (Mg m^{-3}):			
0 to 10 cm	1.3	1.3 – 1.4	1.4 – 1.5
10 to 20 cm	1.3	1.3 – 1.4	1.4 – 1.5
20 to 30 cm	1.3	1.3 – 1.4	1.4 – 1.5

(3) Chemical properties

Chemical properties change within and between soil profiles of the erosion classes. Substantial changes occur in the topsoil layers. Exchangeable basic cations, cation exchange capacity and pH increase with increasing erosion severity. Organic matter contents fluctuate with increasing erosion severity (table 5.7).

Table 5.7 Chemical properties of the erosion classes on Vertisols

Chemical properties	Erosion classes		
	Slightly eroded	Moderately eroded	Severely eroded
Organic matter content (%):			
-surface horizons	0.6 – 1	0.4 – 0.7	1 – 1.3
-subsurface horizons	0.3 – 0.5	0.2 – 0.4	0.4 – 0.5
Carbon/nitrogen ratio:			
-surface horizons	8.3 – 11.4	4.2 – 5.6	9.6 – 9.7
-subsurface horizons	6.8 – 8.3	2.4 – 3.5	5.3 – 7.8
P_2O_5 Bray II (cmol kg^{-1} of soil)			
-surface horizons	1 – 4	3 – 23	6 – 12
-subsurface horizons	1 – 2	2 – 22	2 – 4
Fe_2O_3 free iron (%)			
-surface horizons	1.4 – 1.5	1.3 – 1.9	1.5 – 1.7
-subsurface horizons	1.4 – 1.5	1.3 – 1.9	1.3 – 1.5
Exchangeable basic cations (cmol (+) kg^{-1}):			
-surface horizons	21 – 27.7	15.6 – 21.5	21.7 – 30.6
-subsurface horizons	22.8 – 30	21.2 – 32.2	22.8 – 35.6
Cation exchange capacity (cmol (+) kg^{-1}):			
-surface horizons	9.3 – 29	10.3 – 33	19.5 – 33.9
-subsurface horizons	16.7 - 23	21.1 – 34.7	22 – 47.5
pH (1:2.5 soil/water suspension):			
-surface horizons	7.2 – 7.7	7.8 – 8.1	8.1 – 8.5
-subsurface horizons	7.8 – 8.8	8.3 – 8.7	9.2 – 9.4

For instance, on slightly eroded Vertisols, organic matter contents vary from 0.6 to 1%, sum of exchangeable basic cations varies from 21 to 27.7 cmol (+) kg^{-1} of soil, cation exchange capacity oscillates between 9.3 and 29 cmol (+) kg^{-1} of soil, and the pH values range from 7.2 to 7.7. On severely eroded Vertisols, organic matter contents vary from 1 to 1.3%, sum of exchangeable basic cations varies from 21.7 to 30.6 cmol (+) kg^{-1} of soil, cation exchange capacity ranges between 19.5 and 33.9 cmol (+) kg^{-1} of soil, and the pH values range from 8.1 to 8.5. On average, variations in soil properties with increasing erosion severity on Vertisols can be explained by the sensitivity of the soil properties to changes caused by erosion (figure 5.3). Originally, the topsoil layers of Vertisols exhibit high clay contents. At the intermediate stage of erosion (on moderately eroded Vertisols), the sand and gravel contents increase due to selective removal of clay. Organic matter contents associated with the clay fraction decrease. This results in loss of soil cohesion, which enhances erosion of the sand fraction in the topsoil layers, especially during heavy rainfall events.

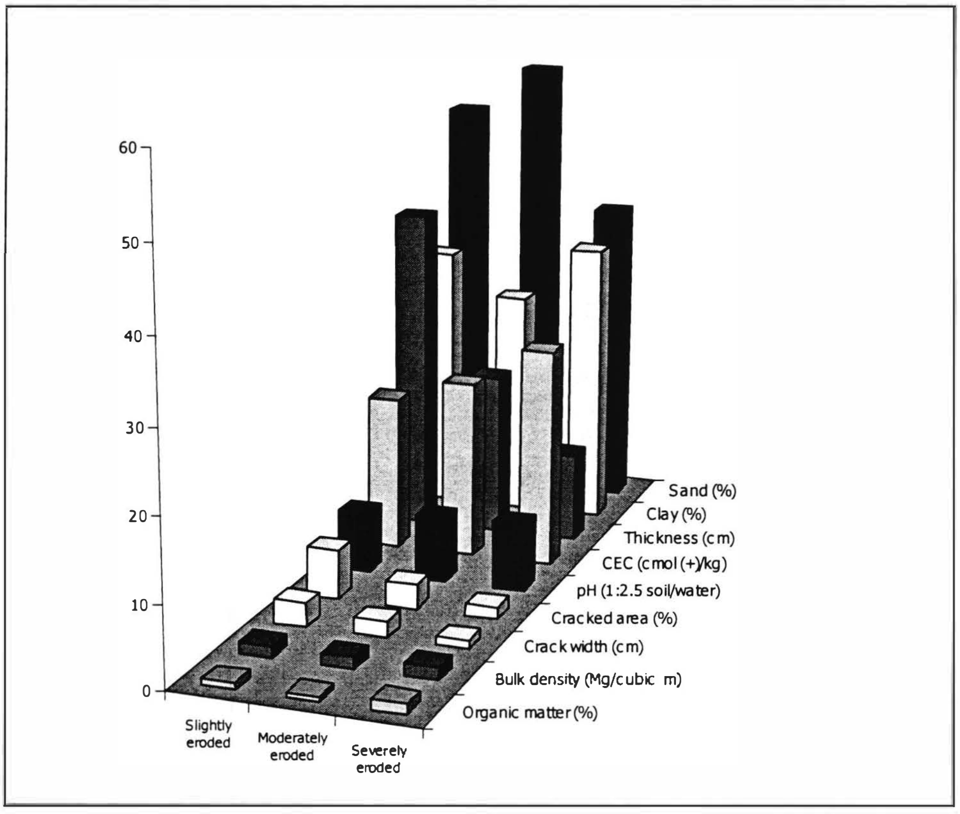


Figure 5.3 Average values of selected topsoil properties within erosion classes on Vertisols

The removal of the sandy topsoil is accompanied by the exposure of massive, compact and clayey subsoil layers, with increased bulk density and few cracks at the latter stage of erosion (on severely eroded Vertisols). The increase of exchangeable basic cations, cation exchange capacity and pH with soil depth and with increasing erosion severity can be attributed to the parent material (gneiss). In fact, the deeper a soil horizon, the more similar are its properties to those of the parent material. Similarly, as the surface horizons are eroded, the depth to the C horizon decreases, which affects the properties of the topsoil layers. Baver et al. (1972), Frye et al. (1982), Larson et al. (1985) and Seiny (1990) report similar results.

5.2.3 Inceptisols

Inceptisols show incipient horizonation. However, many soil properties change according to erosion severity. Three erosion classes were identified: (1) slightly eroded, (2) moderately eroded, and (3) severely eroded. Less eroded soils are on nearly level to gently sloping treads (1 to 2% slope) of the glacis-terraces in the plain, on rolling summits (8 to 9% slope) of the "half-orange" hills in the peneplain, and on hilly to very steep footslopes (12 to 20% slope) of the mountain where terraces have been constructed. More eroded soils are on the escarpment of the plateau, on undulating risers (3 to 5% slope) of the glacis-terraces in the plain, and on areas between the low rounded hills near drainage ways, in the peneplain.

(1) Morphological properties

Substantial changes in the properties occur in the topsoil layer of the erosion classes. The thickness decreases, the colour is lighter and the structure is coarser or massive, with increasing erosion severity. For instance, on slightly eroded Inceptisols, surface horizons are brown (7.5YR 5/2, dry) to grayish brown (2.5Y 5/2, dry), 5 to 12 cm thick, with massive primary structure breaking into single grains. On severely eroded Inceptisols, surface horizons are pale brown (10YR 6/3, dry) to olive (5Y 5/3, dry), 3 to 7 cm thick, with massive primary structure breaking into subangular blocky secondary structure (table 5.8).

Table 5.8 Morphological properties of the erosion classes on Inceptisols

Morphological properties	Erosion classes		
	Slightly eroded	Moderately eroded	Severely eroded
Thickness (cm):			
-surface horizons	5 – 12	4 – 10	3 – 7
-solum	> 150	100 – 150	< 100
Colour (dry):			
-surface horizons	brown to grayish brown	brown to yellowish brown	pale brown to olive
-subsurface horizons	grayish brown to olive	yellowish brown to brownish yellow	grayish brown to olive
Structure:			
-surface horizons	massive to single-grained	massive to subangular blocky	massive to subangular bl.
-subsurface horizons	prismatic or subangular bl.	prismatic, subangular bl. or massive	subangular bl. or massive

(2) Physical properties

Physical properties in the topsoil layers change according to erosion classes. The texture is coarser with increasing erosion severity. On slightly eroded soils, clay content in the surface horizons varies from 5 to 31%, with loamy sand, sandy clay loam or clay texture. The bulk density varies from 1.4 to 1.7 Mg m^{-3}. On severely eroded soils, clay content in the surface horizons varies between 5 and 23%, with sandy clay loam texture. The bulk density varies from 1.4 to 1.6 Mg m^{-3} (table 5.9).

Table 5.9 Physical properties of the erosion classes on Inceptisols

Physical properties	Erosion classes		
	Slightly eroded	Moderately eroded	Severely eroded
Clay content (%):			
-surface horizons	5 – 31	7 – 26	5 – 23
-subsurface horizons	26 – 39	13 – 32	11 – 27
Silt content (%):			
-surface horizons	11 – 22	22 – 25	16 – 21
-subsurface horizons	18 – 20	13 – 30	5 – 26
Sand content (%):			
-surface horizons	44 – 84	48 – 70	57 – 79
-subsurface horizons	41 – 56	42 – 72	45 – 83
Textural class (USDA):			
-surface horizons	loamy sand to clay	sandy loam to sandy clay loam	sandy clay loam
-subsurface horizons	sandy clay loam to clay	sandy loam to loamy sand	sandy clay loam
Coarse particles (%):			
-surface horizons	5 – 29	2 – 14	4 – 31
-subsurface horizons	5 – 34	2 – 31	11 – 47
Bulk density (Mg m^{-3}):			
0 to 10 cm	1.4 – 1.7	1.5 – 1.6	1.4 – 1.6
10 to 20 cm	1.4 – 1.7	1.4 – 1.6	1.4 – 1.6
20 to 30 cm	1.4 – 1.7	1.3 – 1.4	1.4 – 1.6

(3) Chemical properties

Chemical properties change according to erosion classes. Considerable changes occur in the topsoil layers. For instance, on slightly eroded soils, organic matter contents vary from 0.8 to 1.7%, sum of exchangeable basic cations varies from 9.6 to 21.5 cmol (+) kg^{-1} of soil, cation exchange capacity varies from 8 to 22.3 cmol (+) kg^{-1} of soil, and the pH values range from 7.2 to 7.3. On severely eroded soils, organic matter contents vary from 0.7 to 0.9%, sum of exchangeable basic cations varies from 9.8 to 23.8 cmol (+) kg^{-1} of soil, cation exchange capacity varies from 11.2 to 24.1 cmol (+) kg^{-1} of soil, and the pH values range from 7.3 to 7.5 (table 5.10).

Table 5.10 Chemical properties of the erosion classes on Inceptisols

Chemical properties	**Erosion classes**		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Organic matter content (%):			
-surface horizons	0.8 – 1.7	0.6 – 0.7	0.7 – 0.9
-subsurface horizons	0.6 – 1.1	0.1 – 0.7	0.2 – 0.7
Carbon/nitrogen ratio:			
-surface horizons	9.6 – 12.5	5.4 – 8	6.7 – 8.8
-subsurface horizons	6.7 – 9.3	1.6 – 7	4.3 – 7
P_2O_5 Bray II (cmol kg^{-1} of soil):			
-surface horizons	3 – 22	7 – 45	4 – 6
-subsurface horizons	3 – 5	11 – 64	3 – 10
Fe_2O_3 free iron (%):			
-surface horizons	1.1 – 1.6	1.1 – 1.7	0.8 – 2.4
-subsurface horizons	1.3 – 2.2	1.4 – 1.9	1.5 – 1.9
Exchangeable basic cations (cmol (+) kg^{-1}):			
-surface horizons	9.6 – 21.5	12.6 – 17.8	9.8 – 23.8
-subsurface horizons	16.8 – 25.4	14.5 – 22.3	16.7 – 25.7
Cation exchange capacity (cmol (+) kg^{-1}):			
-surface horizons	8 – 22.3	11.6 – 20.9	11.2 – 24.1
-subsurface horizons	10.1 - 27	12.4 - 24	18.8 – 26.5
pH (1:2.5 soil/water suspension):			
-surface horizons	7.2 – 7.3	7.1 – 8	7.3 – 7.5
-subsurface horizons	8.5 – 8.9	6.7 – 8.7	7.7 – 9.6

On average, clay and organic matter contents decrease with increasing erosion severity, whereas cation exchange capacity and pH increase with increasing erosion severity. These variations can be attributed to interrelationships among soil properties and selective erosion. Selective erosion of clay increases sand content. Organic matter contents associated with the clay fraction consequently decreases. As the surface horizons are eroded, the depth to the C horizon decreases, affecting the properties of the topsoil layer and causing an increase in cation exchange capacity and pH (figure 5.4).

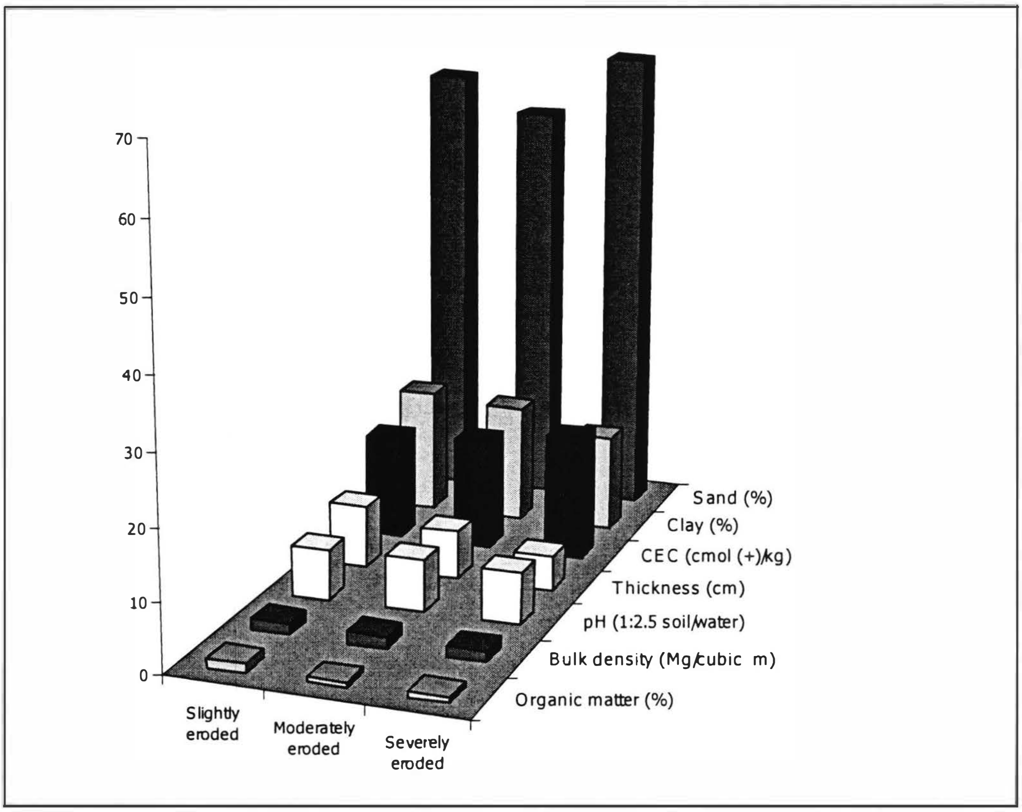


Figure 5.4 Average values of selected topsoil properties within erosion classes on Inceptisols

5.2.4 Entisols

The properties of the Entisols vary according to their origin and erosion severity. Three erosion classes were identified: (1) slightly eroded, (2) moderately eroded, and (3) severely eroded. Slightly and moderately eroded Entisols are along the valleys, whereas severely eroded Entisols are on the steep slopes of the mountains and hillands.

(1) Morphological properties

Morphological properties of the Entisols, found along the valleys, change according to erosion classes. Substantial changes occur in the topsoil layers. For instance, on slightly eroded Entisols, the topsoil layers are dark brown (10YR 3/3, dry) to pale brown (10YR 6/3, dry), 10 to 15 cm thick, with massive primary structure breaking into single grains. On moderately eroded soils, the topsoil layers are brown (10 YR 6/3, dry), 5 to 16 cm thick, with massive primary structure breaking into single grains. On severely eroded Entisols found on steep slopes of the highlands, the soil profile consists of an A horizon laying on the bedrock or a C horizon. It is 5 to 16 cm thick, brown (10YR 5/3, dry), with subangular blocky or granular structure (table 5.11).

Table 5.11 Morphological properties of the erosion classes on Entisols

Morphological properties	**Erosion classes**		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Thickness (cm):			
-surface horizons	10 – 15	8 – 14	5 – 16
-solum	75 - 100	75 – 100	< 20
Colour (dry):			
-surface horizons	dark brown to pale brown	pale brown	brown
-subsurface horizons	yellowish brown to grayish brown	yell. brown to pale brown	-
Structure:			
-surface horizons	massive to granular	massive to granular	subangular bl. or granular
-subsurface horizons	massive or platy to granular	massive or platy to granular	-

(2) Physical properties

Physical properties vary considerably according to erosion classes. Substantial changes occur in the topsoil layers. On slightly eroded Entisols, clay contents vary between 3 and 6%, with loamy sand texture, and the bulk density varies from 1.4 to 1.5 Mg m^{-3}. On severely eroded Entisols, clay contents vary between 5 and 9%, with sandy loam texture, and high coarse particle contents (45 to 59%). The bulk density varies from 1.6 to 1.8 Mg m^{-3} (table 5.12).

Table 5.12 Physical properties of the erosion classes on Entisols

Physical properties	**Erosion classes**		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Clay content (%):			
-surface horizons	3 – 6	3 – 7	5 – 9
-subsurface horizons	1 – 35	1 – 5	-
Silt content (%):			
-surface horizons	6 – 8	15 – 17	7 – 10
-subsurface horizons	1 – 47	1 – 8	-
Sand content (%):			
-surface horizons	75 – 82	70 – 76	60 – 90
-subsurface horizons	13 – 91	80 – 98	-
Textural class (USDA):			
-surface horizons	loamy sand	sandy loam	loamy sand
-subsurface horizons	sand to sandy clay loam	sand to loamy sand	-
Coarse particles (%):			
-surface horizons	1 – 3	1 – 3	45 – 59
-subsurface horizons	1 – 3	1 – 30	-
Bulk density (Mg m^{-3}):			
0 to 10 cm	1.4 – 1.5	1.4 – 1.5	1.6 – 1.8
10 to 20 cm	1.4 – 1.5	1.4 – 1.5	-
20 to 30 cm	1.4 – 1.5	1.4 – 1.5	-

(3) Chemical properties

Chemical properties change within and between soil profiles of the erosion classes. Considerable changes occur in the topsoil layers. For instance, organic matter contents vary from 0.3 to 0.6%, from 0.8 to 1.3%, and from 0.5 to 0.7%, on slighly, moderately and severely eroded soils, respectively. Similarly, cation exchange capacity varies from 8.6 to 19.8 cmol (+) kg^{-1} of soil, from 5 to 12.4 cmol (+) kg^{-1} of soil, and from 8.3 to 54.3 cmol (+) kg^{-1} of soil, respectively (table 5.13).

Table 5.13 Chemical properties of the erosion classes on Entisols

Chemical properties	Erosion classes		
	Slightly eroded	Moderately eroded	Severely eroded
Organic matter (%):			
- surface horizon	0.3 – 0.6	0.8 – 1.3	0.5 – 0.7
- subsurface horizon	0.1 – 5.6	0.2 – 0.8	-
C/N ratio:			
- surface horizon	1.5 – 5	5.3 – 10.6	3.1 – 4.7
- subsurface horizon	2 – 10.2	4.1 – 8	-
P_2O_5-Bray II (cmol kg^{-1}):			
- surface horizon	35 – 38	10 – 16	35 – 43
- subsurface horizon	22 – 62	13 – 11	-
Fe_2O_3-free iron (%):			
- surface horizon	1.1 – 1.5	0.8 – 1	1.1 – 2.1
- subsurface horizon	1 – 3	0.5 – 1.2	-
Exchangeable basic cations (cmol (+) kg^{-1}):			
- surface horizon	11.7 – 13.5	5.1 – 9.6	8.8 – 52.9
- subsurface horizon	6.3 – 30.2	1.7 – 25.9	-
Cation exchange capacity (cmol (+) kg^{-1}):			
- surface horizon	8.6 – 19.8	5 – 12.4	8.3 – 54.3
- subsurface horizon	5.2 - 33	1.5 – 27.8	-
pH (1:2.5 soil/water suspension):			
- surface horizon	7.8 – 8.1	5.9 – 6.8	6.6 – 8.2
- subsurface horizon	7.1 – 8.5	6.4 – 7.7	-

On average, the topsoil layer properties fluctuate with increasing erosion severity, reflecting the nature of the alluvial deposits or that of the hard bedrock (figure 5.5).

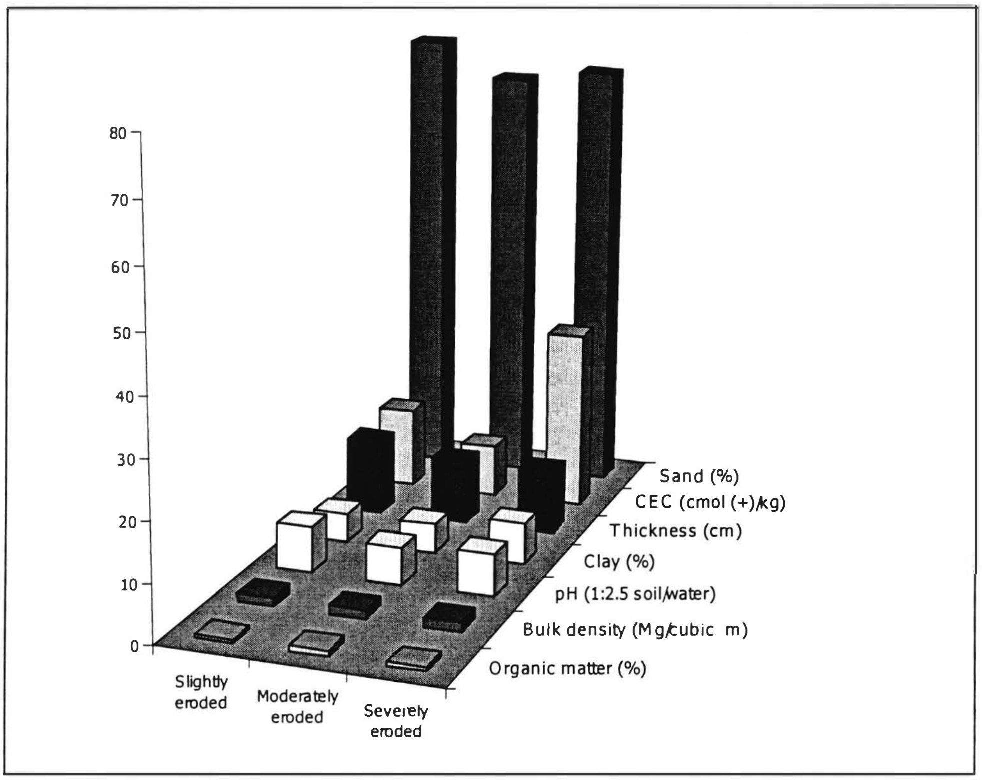


Figure 5.5 Average values of selected topsoil properties within erosion classes on Entisols

5.2.5 Planosols

In the Gawar area, land use planners and extentionists adopt soil names borrowed from different soil classification systems, as long as these soil names provide prominent characteristics, that are easily observable in the field and understandable to the farmers. For instance, soil names, such as Planosols from the FAO soil classification and "Hardé" from the local soil classification are preferred to Alfisols from USDA-Soil Taxonomy.

Planosols have one or more upper horizons with a relatively low clay content, which abruptly overlay a deeper and less permeable horizon with considerably high clay content. However, many soil properties change according to erosion classes. Three erosion classes were identified: (1) slightly eroded, (2) moderately eroded, and (3) severely eroded. Slightly eroded soils are on nearly level to gently sloping treads (0 to 3% slope) of the glacis-terraces, whereas moderately and severely eroded soils are on undulating to rolling risers (2 to 13% slope) of the glacis-terraces, in the plain.

(1) Morphological properties

Substantial changes in the properties occur in the topsoil layer of the erosion classes. The thickness decreases, the colour is lighter and the structure is coarser or massive, as the erosion severity increases. For instance, on slightly eroded Planosols, surface horizons are brown (10YR 5/3, dry) to very pale brown (10YR 7/3, dry), 10 to 40 cm thick, with massive primary structure breaking into single grains. A white (10YR 8/1, dry), single-grained eluvial horizon of 5 to 10 cm thick occurs at the bottom of the A horizon. On severely eroded Planosols, surface horizons are yellowish brown (10YR 5/4, dry), 3 to 5 cm thick, with columnar or subangular blocky structure. The eluvial horizon is absent (table 5.14). Surface horizons of less eroded soils absorb water more readily than those of more eroded soils.

Table 5.14 Morphological properties of the erosion classes on Planosols

Morphological properties	**Erosion classes**		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Thickness (cm)			
-surface horizons	15 – 40	8 – 20	3 – 5
-eluvial horizon	5 - 10	5 - 10	absent
-solum	> 150	100 – 150	< 100
Colour (dry)			
-surface horizons	brown to pale brown	reddish brown to reddish yellow	yellowish brown
-eluvial horizon	white	white	-
-subsurface horizons	yellow to yellowish br.	reddish yellow to brownish gray	yellowish br. to brownish gray
Structure			
-surface horizons	massive to single-grained	massive to granular	columnar or subangular blocky
-eluvial horizon	single-grained	single-grained	-
-subsurface horizons	columnar or massive	columnar or massive	massive

(2) Physical properties

Physical properties in the topsoil layers change according to erosion classes. The texture is finer, the bulk density increases and the coarse fragment contents increase, with increasing erosion severity (table 5.15).

Table 5.15 Physical properties of the erosion classes on Planosols

Physical properties	Erosion classes		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Clay content (%)			
-surface horizons	7 – 22	10 – 12	14 – 25
-eluvial horizon	7 -11	7 – 11	-
-subsurface horizons	30 – 36	30 – 37	22 – 38
Silt content (%)			
-surface horizons	15 – 25	12 – 22	15 – 28
-eluvial horizon	30 - 33	30 – 33	-
-subsurface horizons	16 – 20	12 – 21	15 – 68
Sand content (%)			
-surface horizons	60 – 70	65 – 76	45 – 68
-eluvial horizon	59 - 65	59 - 65	-
-subsurface horizons	45 – 50	40 – 52	33 – 57
Textural class			
-surface horizons	sandy loam to sandy clay loam	sandy loam	sandy loam
-eluvial horizon	sandy loam	sandy loam	-
-subsurface horizons	sandy clay	sandy clay to clay loam	sandy clay loam to clay loam
Coarse particles (%)			
-surface horizons	2 – 4	10 – 15	10 – 15
-subsurface horizons	10 – 15	15 – 20	10 – 26
Bulk density (Mg m^{-3})			
0 to 10 cm	1.4 – 1.6	1.5 – 1.6	1.6 – 1.7
10 to 20 cm	1.4 – 1.6	1.5 – 1.6	1.6 – 1.7
20 to 30 cm	1.4 – 1.6	1.5 – 1.6	1.6 – 1.7

For instance, on slightly eroded Planosols, clay content in the surface horizons varies from 7 to 22%, with sandy loam to sandy clay loam texture. Coarse particle contents are less than 5%. The bulk density varies from 1.4 to 1.6 Mg m^{-3}. On severely eroded Planosols, clay content in the surface horizons varies between 14 and 25%, with sandy loam texture and coarse particle contents varying between 10 and 15%. Iron and manganese nodules are common. Coarse particle contents range between 10 and 26%. The bulk density varies from 1.6 to 1.7 Mg m^{-3}.

(3) Chemical properties

Chemical properties change within and between soil profiles of the erosion classes. Drastic changes occur in the topsoil layers. Organic matter contents, cation exchange capacity and pH increase with increasing erosion severity. For instance, on slightly eroded Planosols, organic matter contents vary from 0.1 to 0.5%, cation exchange capacity ranges from 4.1 to 7.7 cmol (+) kg^{-1} of soil and the pH values oscillate between 5.8 and 6.2. On severely eroded Planosols, organic matter contents vary from 0.8 to 1.7%, cation exchange capacity varies from 10.2 to 19 cmol (+) kg^{-1} of soil, and the pH values range from 6 to 6.8 (table 5.16).

Table 5.16 Chemical properties of the erosion classes on Planosols

Physical properties	Erosion classes		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Organic matter content (%):			
-surface horizons	0.1 – 0.5	0.2 – 0.6	0.8 – 1.7
-eluvial horizon	0 – 0.1	0 – 0.1	-
-subsurface horizons	0.1 – 0.2	0.1 – 0.3	0.3 – 1.1
Carbon/nitrogen ratio:			
-surface horizons	1.6 – 4.8	2.4 – 5.5	5.1 – 12.5
-eluvial horizon	1 – 1.3	1 – 1.3	-
-subsurface horizons	1 – 2	1.6 – 3.4	3 – 12.2
P_2O_5 Bray II (cmol kg^{-1} of soil):			
-surface horizons	1 – 5	2 – 5	2 – 3
-eluvial horizon	0.5 - 1	0.5 - 1	-
-subsurface horizons	0.5 – 1	1 – 7	1 – 7
Fe_2O_3 free iron (%):			
-surface horizons	1.2 – 2	1.1 – 1.3	1.3 – 2.3
-eluvial horizon	1.2 – 1.6	1.2 – 1.6	-
-subsurface horizons	2.1 – 2.3	1.4 – 1.8	1.5 – 2
Exchangeable basic cations (cmol (+) kg^{-1}):			
-surface horizons	3 – 6	3 – 5	8.4 – 17.3
-eluvial horizon	3 - 4	3 – 4	-
-subsurface horizons	10 – 16	14 – 26	10 – 30
Cation exchange capacity (cmol (+) kg^{-1}):			
-surface horizons	4.1 – 7.7	3 – 7.3	10.2 – 19
-eluvial horizon	4 – 5	4 – 5	-
-subsurface horizons	6.3 – 15.9	11.3 - 28	9.7 – 29.8
pH (1:2.5 soil/water suspension):			
-surface horizons	5.8 – 6.2	6.4 – 6.7	6 – 6.8
-eluvial horizon	5.6 – 5.8	5.6 – 5.8	-
-subsurface horizons	6.1 – 7.8	7.4 – 9.3	6.7 – 9.4

On average, variations in soil properties with increasing erosion severity on Planosols can be explained by interrelationships among the properties, selective erosion and land use (figure 5.6). In fact, at the intermediate stage of erosion (on moderately eroded Planosols), the sand and gravel contents increase due to selective removal of clay. This results in loss of soil cohesion, which enhances erosion of the sand fraction, especially during heavy rainfall events. The removal of the sandy topsoil layers is accompanied by the exposure of compact and clayey subsoil layers at the latter stage of erosion (on severely eroded Planosols). Eroded Planosols are used for grazing, which increases organic matter contents due to animal excreta. High organic matter contents increase the cation exchange capacity of eroded Planosols.

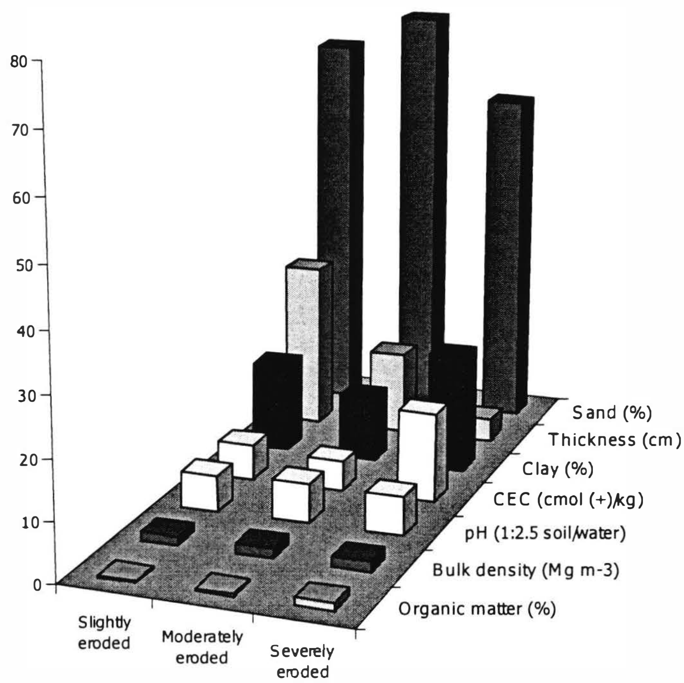


Figure 5.6 Average values of selected topsoil properties within erosion classes on Planosols

5.2.6 Variation of soil properties between soil types within erosion classes

Variations in the properties between soil types change according to erosion classes. On average, drastic changes occur in the topsoil layer characteristics. For instance, on slightly eroded soils, the organic matter content is high on Inceptisols (1.3%), small on Planosols (0.3%) and intermediate on Alfisols (0.8%) and Vertisols (0.8%). The clay content is high on Vertisols (33%), small on Alfisols and Entisols (6 and 5%, respectively), and intermediate on Inceptisols and Planosols (18 and 15%, respectively). The cation exchange capacity is high on Alfisols and Vertisols (21 and 19 cmol (+) kg^{-1} of soil, respectively), small on Planosols (6 cmol (+) kg^{-1} of soil) and intermediate on Inceptisols and Entisols (15 and 14 cmol (+) kg^{-1} of soil, respectively) (figure 5.7).

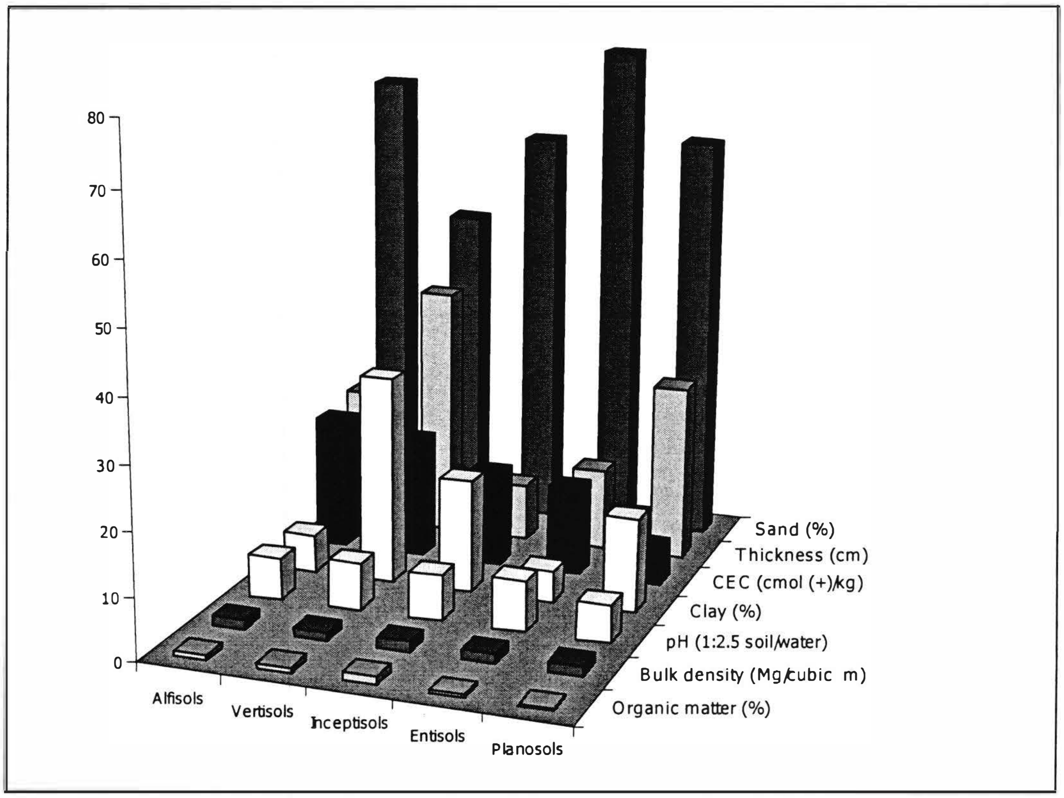


Figure 5.7 Variations of the properties between soil types within the slightly eroded soil class

On moderately eroded soils, the organic matter content is high on Entisols and Inceptisols (1 and 0.7%, respectively), small on Alfisols (0.3%) and intermediate on Vertisols (0.6%). The clay content is high on Vertisols (28%), small on Entisols (5%), and intermediate on Inceptisols (17%). The cation exchange capacity is high on Vertisols (22 cmol (+) kg^{-1} of soil), small on Planosols (5 cmol (+) kg^{-1} of soil), and intermediate on Alfisols and Entisols (16 cmol (+) kg^{-1} of soil) (figure 5.8).

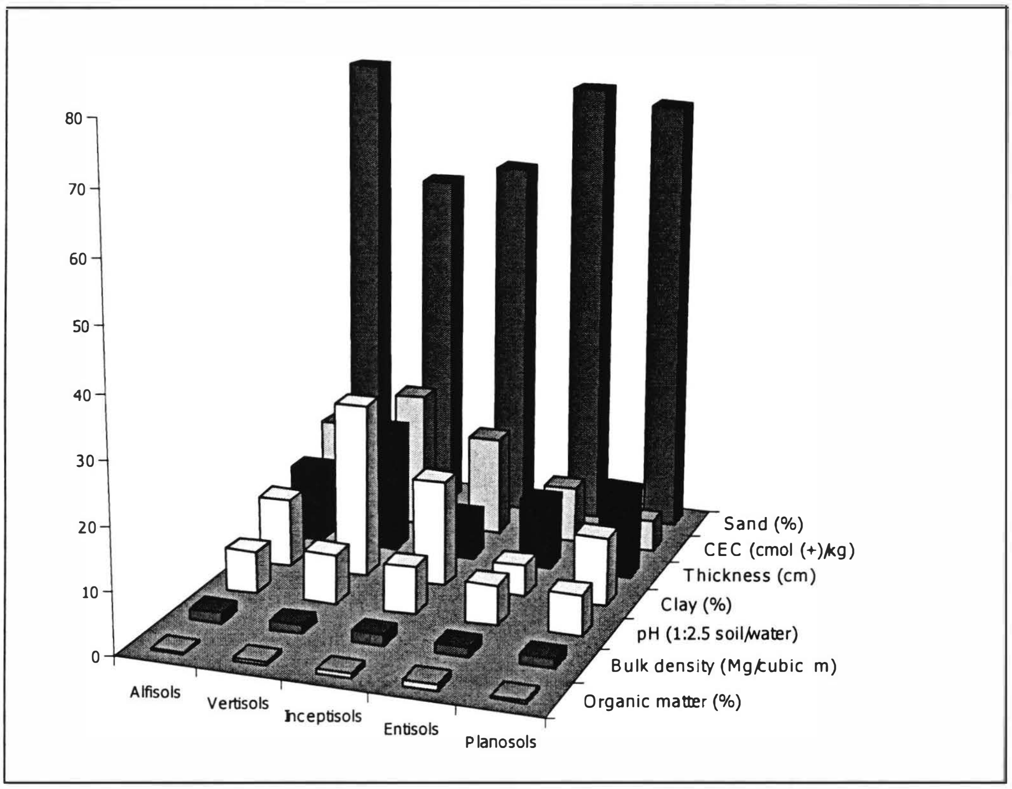


Figure 5.8 Variations in the properties between soil types within the moderately eroded soil class

On severely eroded soils, the organic matter content is high on Planosols and Vertisols (1.3 and 1.2%, respectively), small on Alfisols (0.6%) and intermediate on Inceptisols (0.8%). The clay content is high on Vertisols (35%), small on Entisols (7%) and intermediate on Alfisols and Planosols (24 and 20%, respectively). The cation exchange capacity is high on Entisols (24 cmol (+) kg^{-1} of soil), small on Alfisols (10 cmol (+) kg^{-1} of soil) and intermediate on Vertisols (27 cmol (+) kg^{-1} of soil) (figure 5.9).

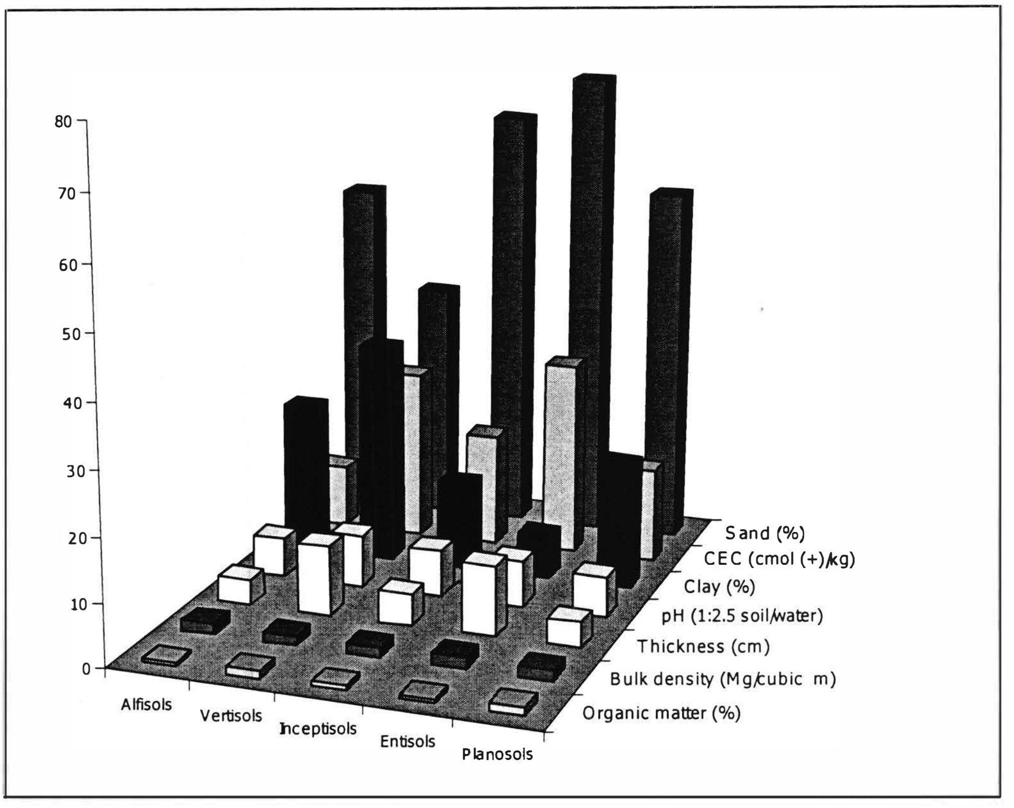


Figure 5.9 Variations in the properties between soil types within the severely eroded soil class

On Alfisols and Planosols, variations in clay content in the surface horizon can be explained by the fact that the removal of the topsoil exposes clayey subsurface layers at the surface, which causes an increase in clay content with increasing erosion severity. In general, variations of clay content in the surface horizon are reduced on severely eroded soils, indicating that erosion minimizes the differential behaviour between soil types. On Vertisols, Inceptisols and Entisols, increased cation exchange capacity with increasing erosion severity can be due to the proximity of the parent materials, which influences the chemical properties of the topsoil layer. More eroded Planosols are devoted to grazing, which increases the organic matter content.

5.2.7 Conclusion

In general, chemical soil properties improve whereas morphological and physical soil properties degrade, with increasing erosion severity. For instance, exchangeable basic cations, cation exchange capacity and pH increase in the topsoil layers with increasing erosion severity, because of the proximity to the parent material. As erosion proceeds, the depth to the C horizon decreases, which influences the chemical properties of the topsoil layers. Baver et al. (1972), Frye et al. (1982), Foster et al. (1985), Larson et al. (1985) and Seiny (1990) report similar results. Organic matter content also increases with increasing erosion severity, which can be attributed to land use. More eroded soils are devoted to fallow or grazing, which increases the organic matter status of the topsoil layers. However, more eroded soils are subjected to frequent crop failure, indicating that morphological and physical soil properties are the major factors that determine crop production in the Gawar area. For instance, increased erosion causes a decrease of the thickness of the topsoil layer, which reduces the rooting depth of crops. Similarly, the topsoil layers become clayey, compact and massive, which decreases infiltration and reduces the water holding capacity of the soil due to reduced porosity. Batchelder and Jones (1972) point out that the most serious erosion damage is the reduction in the water holding capacity of the soils. In fact, morphological and physical soil properties regulate the water circulation and control the soil moisture contents for plant growth. The inadequate soil moisture in the more eroded soils can be improved by implementing agricultural practices that aim at controlling erosion, conserving water by storage and improving infiltration.

5.3 VARIABILITY OF SELECTED SOIL PROPERTIES

In the previous section, the erosion classes of the main soil types in the Gawar area were characterized using the properties of the topsoil layers. The quality of the soil properties in the surface horizons controls the productive capacity of the soils and dictates the farmer's decision on the type of land use to undertake. To assess the variability of the soil properties between and within map units, descriptive statistics were applied to soil properties measured on composite samples from the topsoil layer in twelve selected map units. Seven composites, each made from five individual samples, were collected along three directions with an angle of 120 degrees at 5 m intervals from the point where rainfall simulation experiments were performed. Statistical estimates, such as the arithmetic mean, range, standard deviation and coefficient of variation, were calculated to characterize the variations of the selected soil properties.

5.3.1 Variability of soil properties within and between soil types

Descriptive statistics were applied to three data sets, including: (1) 66 values of each selected soil property of the topsoil layer measured from each class of slightly, moderately and severely eroded Alfisols and Vertisols, respectively; (2) 44 values of each selected soil property of the topsoil layer measured from each class of slightly and moderately eroded Inceptisols; and (3) 44 values of each selected soil property of the topsoil layer measured from each class of slightly and severely eroded Planosols. To compare soil variability between soil properties within soil types, the coefficients of variation were determined for each soil property within each soil type. Data indicate that the degree of variability changes considerably with soil properties (table 5.17).

Table 5.17 Variations of soil properties within soil types

Soil types	Properties of the topsoil layer	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)
Alfisols	Thickness (cm)	11.7	2	19	5.33	46
	Coarse particle (%)	4.5	1	14	3.01	67
	Sand (%)	67.9	46.5	80.4	10.69	16
	Clay (%)	15	2.7	47.7	13.09	87
	Organic matter (%)	0.7	4.9	1.2	0.21	30
	pH	6.3	2	7	0.54	9
Vertisols	Thickness (cm)	5.7	1	12	3.25	57
	Coarse particle (%)	32.3	5.2	73	13.53	49
	Sand (%)	39.9	24.8	60.6	6.4	16
	Clay (%)	30.1	16.8	45.3	5.76	19
	Organic matter (%)	1.6	0.8	3	0.71	33
	pH	8	7	9.3	3.25	9
Inceptisols	Thickness (cm)	7.9	1	15	4.35	55
	Coarse particle (%)	21.8	2	48	11.77	54
	Sand (%)	48.5	37.5	63.4	5.95	12
	Clay (%)	26.9	17.3	40.2	5.71	21
	Organic matter (%)	1.4	0.3	2.9	0.93	66
	pH	7.7	7.2	8.8	0.44	6
Planosols	Thickness (cm)	10	2	22	5.8	58
	Coarse particle (%)	11.4	0	35.6	9.69	85
	Sand (%)	62.4	44.4	75.8	8.1	13
	Clay (%)	15.1	2.5	30.6	8.52	56
	Organic matter (%)	0.9	0.5	1.4	0.22	24
	pH	6.4	5.4	8	0.63	10

(1) Variability within soil types

On Alfisols, the values of the coefficient of variation are high for clay and coarse particle contents (87 and 67%, respectively), small for pH (9%), and intermediate for thickness of the topsoil layer (46%) and organic matter contents (30%).

On Vertisols, the thickness of the topsoil layer and the coarse particle content display a high variation (57 and 49%, respectively). The pH exhibits a small variation (9%), whereas clay and organic matter contents show intermediate variations (19 and 33%, respectively).

On Inceptisols, organic matter contents, thickness of the topsoil layer and coarse particle contents display high variations (66, 55 and 54%, respectively). The pH exhibits a small variation (6%). Clay contents show an intermediate variation (21%).

On Planosols, the values of the coefficient of variation are high for coarse particle contents (85%) and small for pH (10%). The thickness of the topsoil layer, clay and organic matter contents display intermediate variations.

In general, the thickness of the topsoil layer and coarse particle contents show high variations, pH shows small variations, whereas organic matter and clay contents show intermediate variations. Variations in soil properties suggest differential sensitivity of these properties to change under erosion. The thickness of the topsoil layer and coarse particle contents can vary considerably over short distances due to land use, land management and selective erosion. Small variations of the pH can be explained by the fact that leaching is not pronounced in these semiarid conditions, causing a uniformity in soil pH values. Briggs and Shishira (1985) report similar results.

(2) Variability between soil types

Alfisols and Planosols exhibit high variations, whereas Vertisols and Inceptisols show small variations (figure 5.10). For instance on Alfisols, the coefficients of variation vary from 9% for pH to 87% for clay. On Planosols, the coefficients of variation vary from 10% for pH to 85% for coarse particle contents. On Vertisols, in contrast, the coefficients of variation vary only from 9% for pH to 57% for the thickness of the topsoil layer. Similarly, the coefficients of variation vary from 6% for pH to 66% for organic matter contents on Inceptisols (table 5.17).

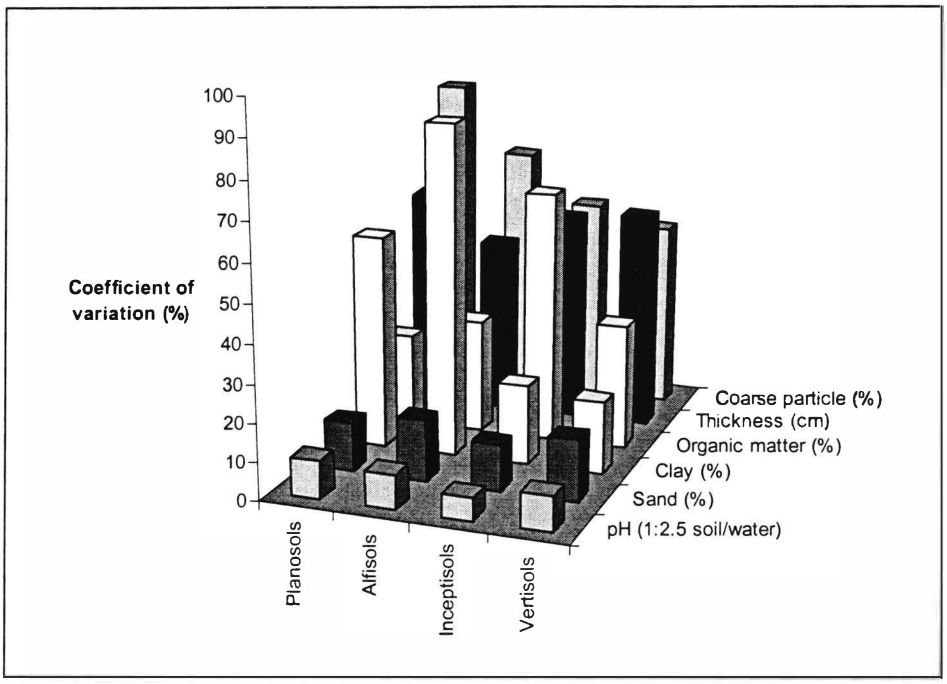


Figure 5.10 Variability of the properties between soil types

The high variability in Alfisols and Planosols can be explained by the fact that these soils show pronounced horizonation, conferring specific characteristics to each soil layer. Local differences due to selective erosion suggest that small erosion can cause substantial changes in soil properties. On Vertisols and Inceptisols, however, weathering and leaching are less effective and the soil layers are still relatively homogeneous, causing small changes under erosion.

Substantial differences in the coefficients of variation of the soil properties suggest that adequate assessment of soil variability may need different numbers of samples for each soil property. Likewise, considerable differences in the coefficients of variation between soil types may entail different sampling schemes for different soil types (Van den Broek et al., 1981; Briggs and Shishira, 1985).

5.3.2 Variability of the soil properties between erosion classes within soil types

(1) Alfisols (table 5.18)

On slightly eroded Alfisols (map unit 15), coarse particle contents have a high coefficient of variation (75%). Clay contents follow, with a coefficient of variation of 36%. Sand contents and pH values show small variations, with coefficients of variation of 6% and 2%, respectively. The thickness of the topsoil layer and organic matter contents show intermediate values of the coefficient of variation. Moderately eroded (map unit 18) and severely eroded Alfisols (map unit 19) demonstrate similar variations.

Table 5.18 Variations of selected soil properties in the topsoil layers of Alfisols

Erosion class	Properties of the topsoil layer	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Map unit
Slightly eroded	Thickness (cm)	15.3	8	19	2.72	18	15
	Coarse particles (%)	4.7	1	12.8	3.52	75	
	Sand (%)	71.2	64.7	80.4	4.26	6	
	Clay (%)	9.7	4.8	14.6	3.49	36	
	Organic matter (%)	0.9	0.8	1.2	0.14	16	
	pH	6.6	6.3	6.9	0.16	2	
Moderately eroded	Thickness (cm)	14.9	10	19	2.29	15	18
	Coarse particles (%)	4	1.2	6.6	1.56	39	
	Sand (%)	77.4	73.8	80.3	1.79	2	
	Clay (%)	4	2.7	5.6	0.63	16	
	Organic matter (%)	0.5	0.4	0.7	0.07	14	
	pH	6.4	6.1	7	0.22	3	
Severely eroded	Thickness (cm)	4.9	2	8	1.53	31	19
	Coarse particles (%)	4.8	1.2	14	3.59	75	
	Sand (%)	55.1	46.5	68.1	7.33	13	
	Clay (%)	31.3	18	47.7	9.11	29	
	Organic matter (%)	0.6	0.3	1	0.18	30	
	pH	5.8	4.9	7	0.64	11	

The values of the coefficient of variation for selected soil properties were compared to highlight the variability between erosion classes on Alfisols and between the Alfisols as a whole and each erosion class. The degrees of variation between erosion classes change according to soil properties. The order of increasing degrees of variation is indicated by moderately eroded < slightly eroded < severely eroded for the organic matter content and thickness of the topsoil layer. This order is moderately eroded < severely eroded < slightly eroded for clay contents. It is slightly eroded < moderately eroded < severely eroded for pH (figure 5.11).

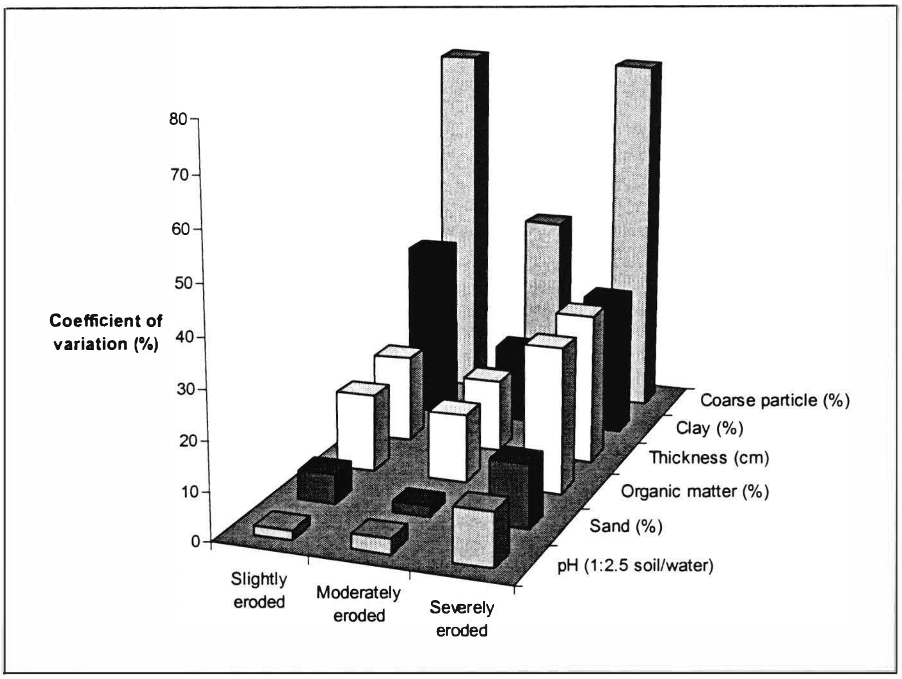


Figure 5.11 Variability of the soil properties between erosion classes on Alfisols

The degree of variation in each of the three erosion classes is small compared to that within the Alfisols as a whole. For instance, the values of the coefficient of variation for clay contents are 36% on slightly eroded Alfisols, 16% on moderately eroded Alfisols, 29% on severely eroded Alfisols, but 87% on the Alfisols as a whole. The thickness of the topsoil layer, sand content and pH exhibit similar behaviour (table 5.19).

Table 5.19 Variations between erosion classes on Alfisols

Properties of the topsoil layer	**Coefficient of variation within erosion classes on Alfisols (%)**			**Coefficient of variation within Alfisols (%)**
	Slightly eroded	**Moderately eroded**	**Severely eroded**	
Thickness (cm)	18	15	31	46
Coarse particle (%)	75	39	75	67
Sand (%)	6	2	13	16
Clay (%)	36	16	29	87
Organic matter (%)	16	14	30	30
pH	2	3	11	9

(2) Vertisols (table 5.20)

On slightly eroded Vertisols (map unit 16), coarse particle contents show a high coefficient of variation (52%). The pH exhibits a small coefficient of variation (3%). Sand contents, thickness of the topsoil layer and organic matter contents display intermediate variations (21, 19 and 18%, respectively). On moderately eroded Vertisols (map unit 20), the values of the coefficient of variation are 37, 31 and 3% for thickness of the topsoil layer, coarse particle contents and pH, respectively. On severely eroded Vertisols (map unit 21), the values of the coefficient of variation are 56, 31 and 4%, for the same properties, respectively. Clay contents and organic matter contents display intermediate variations.

Table 5.20 Variations of selected soil properties in the topsoil layers of Vertisols

Erosion class	Properties of the topsoil layer	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Map unit
Slightly eroded	Thickness (cm)	9.7	5	12	1.88	19	16
	Coarse particle (%)	25.8	5.2	46.7	13.38	52	
	Sand (%)	37.9	24.8	60.6	7.86	21	
	Clay (%)	34.3	16.8	45.3	6.99	20	
	Organic matter (%)	1.6	1.1	2.1	0.28	18	
	pH	7.4	7	8	0.22	3	
Moderately eroded	Thickness (cm)	4.1	2	8	1.53	37	20
	Coarse particle (%)	41.5	23	73	12.72	31	
	Sand (%)	37	30	45	4.01	11	
	Clay (%)	26.4	20	33	3.6	20	
	Organic matter (%)	1.2	0.8	1.8	0.23	19	
	pH	7.8	7.4	8.2	0.23	3	
Severely eroded	Thickness (cm)	3.2	1	6	1.8	56	21
	Coarse particle (%)	29.5	14	44	9.21	31	
	Sand (%)	44.9	38.8	50.7	3.2	7	
	Clay (%)	29.6	23.2	33.9	2.75	9	
	Organic matter (%)	2.1	1.3	3	0.51	24	
	pH	8.9	7.5	9.3	0.35	4	

The variations of the soil properties were compared between erosion classes. The degrees of variation change according to soil properties. For instance, the order of increasing degree of variation is indicated by slightly eroded < moderately eroded < severely eroded for organic matter contents and thickness of the topsoil layer. This order is moderately eroded < slightly eroded < severely eroded for the pH. It is severely eroded < moderately eroded < slightly eroded for clay contents and sand contents (figure 5.12).

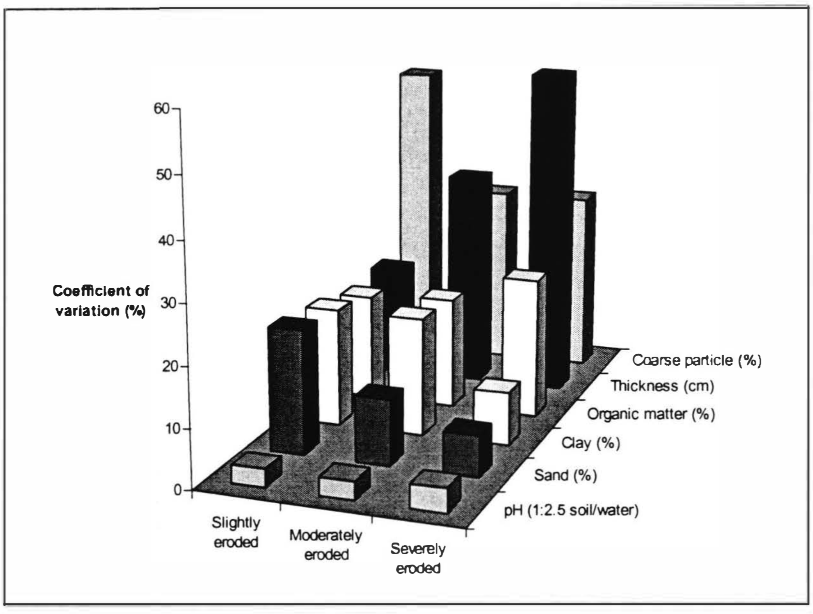


Figure 5.12 Variability of the soil properties between erosion classes on Vertisols

The values of the coefficient of variation for selected soil properties were compared to highlight the variability between Vertisols as a whole and each erosion class. For many properties, the degree of variation is less within each erosion class than within the Vertisols as a whole. For instance, the values of the coefficient of variation for pH are 3% on slightly and moderately eroded Vertisols, 4% on severely eroded Vertisols, but 9% on the Vertisols as a whole. The organic matter contents and thickness of the topsoil layer exhibit similar behaviour (table 5.21).

Table 5.21 Variations between erosion classes on Vertisols

Properties of the topsoil layer	Coefficient of variation within erosion classes on Vertisols (%)			Coefficient of variation within Vertisols (%)
	Slightly eroded	Moderately eroded	Severely eroded	
Thickness (cm)	19	37	56	57
Coarse particle (%)	52	31	31	49
Sand (%)	21	11	7	16
Clay (%)	20	20	9	19
Organic matter (%)	18	19	24	33
pH	3	3	4	9

(3) Inceptisols (table 5.22)

On slightly eroded Inceptisols (map unit 17), the values of the coefficient of variation are high for coarse particle contents (44%), small for pH (5%), and intermediate for clay contents (16%) and organic matter contents (12%). A similar behaviour is observed on moderately eroded Inceptisols (map unit 22), where the values of the coefficient of variation are 63, 5, 28 and 20% for coarse particle contents, pH, organic matter contents and clay contents, respectively.

Table 5.22 Variations of selected soil properties in the topsoil layers of Inceptisols

Erosion class	Properties of the topsoil layer	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Map unit
Slightly eroded	Thickness (cm)	11.8	7	15	1.94	16	17
	Coarse particle (%)	25.3	9	48	11.12	44	
	Sand (%)	49.6	42.8	57.3	4.21	9	
	Clay (%)	24.1	17.3	31.9	3.94	16	
	Organic matter (%)	2.3	1.7	2.9	0.28	12	
	pH	7.5	7.2	8.8	0.36	5	
Moderately eroded	Thickness (cm)	3.9	1	7	1.51	39	22
	Coarse particle (%)	18.2	2	38	11.57	64	
	Sand (%)	47.4	37.5	63.4	7.24	15	
	Clay (%)	29.7	19.6	40.2	5.88	20	
	Organic matter (%)	0.5	0.3	0.8	0.14	28	
	pH	8	7.5	8.6	0.36	5	

The variations of the soil properties were compared between erosion classes. The degrees of variation change according to soil properties. For many soil properties, the degree of variation increases with increasing erosion severity (figure 5.13). For instance, on slightly eroded Inceptisols, the coefficients of variation for sand, organic matter and clay contents are 9, 12 and 16%, respectively. On moderately eroded Inceptisols, the coefficients of variation are 15, 28 and 20%, respectively (table 5.23).

The values of the coefficient of variation for the selected soil properties are small within each erosion class compared to those within the Inceptisols as a whole. For instance, the values of the coefficient of variation for organic matter contents are 12% on slightly eroded Inceptisols, 28% on moderately eroded Inceptisols, but 66% on the Inceptisols in general. The thickness of the topsoil layer and the clay contents show the same trend (table 5.23).

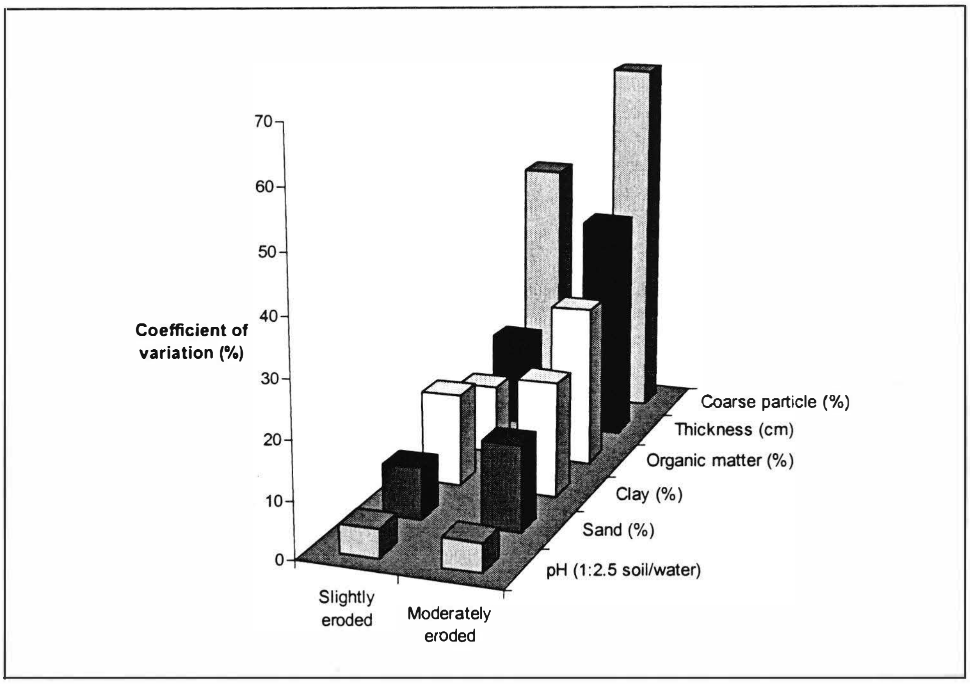


Figure 5.13 Variability of the soil properties between erosion classes on Inceptisols

Table 5.23 Variations between erosion classes on Inceptisols

Properties of the topsoil layer	Coefficient of variation within erosion classes on Inceptisols (%)		Coefficient of variation within Inceptisols (%)
	Slightly eroded	Moderately eroded	
Thickness (cm)	16	39	55
Coarse particle (%)	44	64	54
Sand (%)	9	15	12
Clay (%)	16	20	21
Organic matter (%)	12	28	66
pH	5	5	6

(4) Planosols (table 5.24)

On slightly eroded Planosols (map unit 23), coarse particle contents exhibit a high coefficient of variation (93%). Clay contents follow with 33%. The pH displays a small coefficient of variation (6%). The thickness of the topsoil layer and organic matter contents show intermediate variations. Severely eroded Planosols (map unit 25) display similar behaviour. The values of the coefficient of variation are high for clay contents and coarse particle contents (58 and 56%, respectively). The pH displays a small variation (10%). The thickness of the topsoil layer and organic matter contents show intermediate variations.

Table 5.24 Variations of selected soil properties in the topsoil layers of Planosols

Erosion class	Properties of the topsoil layer	Mean	Minimum	Maximum	Standard deviation	Coefficient of variation (%)	Map unit
Slightly eroded	Thickness (cm)	15.2	10	22	2.84	19	23
	Coarse particle (%)	5.5	1	20.5	5.09	93	
	Sand (%)	66.8	56.7	75.8	4.76	7	
	Clay (%)	12	6.4	18.1	3.99	33	
	Organic matter (%)	1.1	0.8	1.4	0.19	17	
	pH	6.1	5.7	7	0.35	6	
Severely eroded	Thickness (cm)	4.7	2	8	1.65	35	25
	Coarse particle (%)	17.3	4.4	35.5	9.67	56	
	Sand (%)	58	44.4	72.1	8.4	15	
	Clay (%)	18.2	2.5	30.6	10.63	58	
	Organic matter (%)	0.8	0.5	1.1	0.17	21	
	pH	6.8	5.4	8	0.66	10	

Variations of the soil properties between erosion classes of the Planosols were compared. The degree of variation increases with increasing erosion severity (figure 5.14). For instance, on slightly eroded Planosols, the coefficients of variation for pH, organic matter and clay contents are 6, 17 and 33%, respectively. On severely eroded Planosols, the coefficients of variation are 10, 21 and 58%.

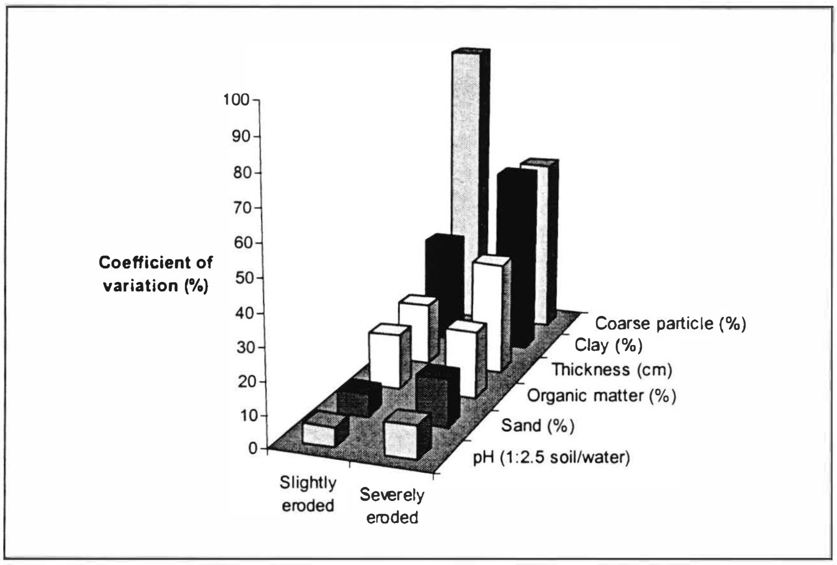


Figure 5.14 Variability of the soil properties between erosion classes on Planosols

For properties, such as the thickness of the topsoil layer and organic matter content, variations within each erosion class are small compared to the variations within the Planosols as a whole (table 5.25).

Table 5.25 Variations between erosion classes on Planosols

Properties of the topsoil layer	Coefficient of variation within erosion classes on Planosols (%)		Coefficient of variation within Planosols (%)
	Slightly eroded	Severely eroded	
Thickness (cm)	19	35	58
Coarse particle (%)	93	56	85
Sand (%)	7	15	13
Clay (%)	33	58	56
Organic matter (%)	17	21	24
pH	6	10	10

5.3.3 Variability of the properties between soil types within erosion classes

The coefficients of variation of the properties between soil types change according to erosion classes. For instance, on slightly eroded soils, the coefficient of variation for the pH is high on Planosols and Inceptisols (6 and 5%, respectively), small on Alfisols (2%) and intermediate on Vertisols (3%). The coefficient of variation for the clay content is high on Alfisols and Planosols (36 and 33%, respectively), small on Inceptisols (16%) and intermediate on Vertisols (20%) (figure 5.15).

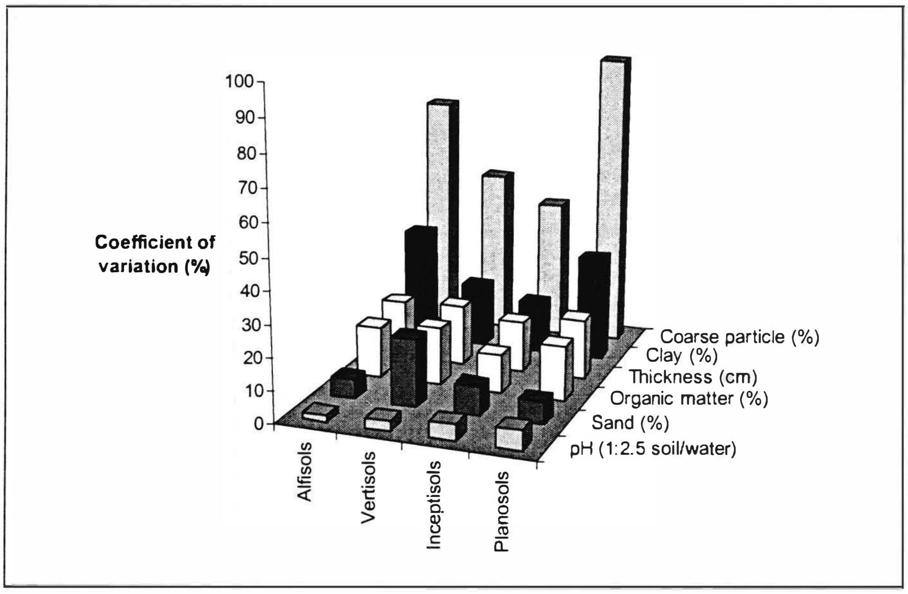


Figure 5.15 Variability of the properties between soil types within the slightly eroded soil class

On moderately eroded soils, the coefficient of variation for the pH is 5% on Inceptisols and 3% on Alfisols and Vertisols. The organic matter content shows similar behaviour. The coefficient of variation for clay content is high on Vertisols and Inceptisols (20% on both) and small on Alfisols (figure 5.16).

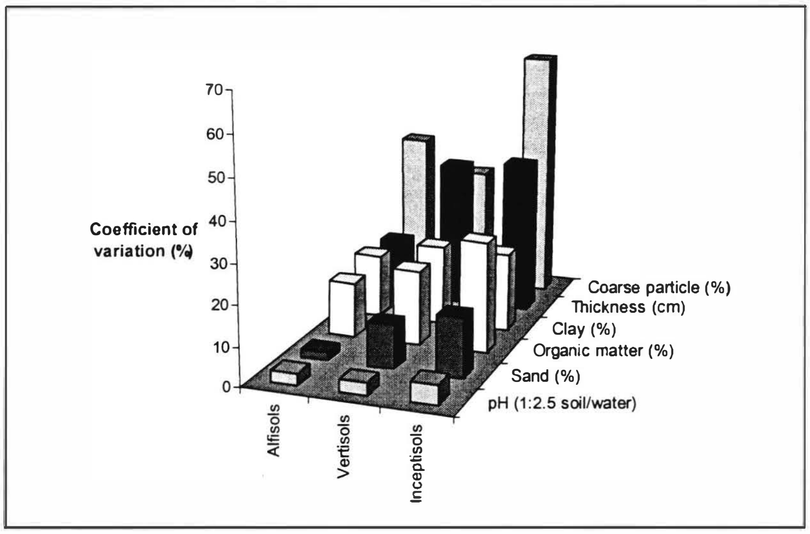


Figure 5.16 Variability of the properties between soil types within the moderately eroded soil class

On severely eroded soils, the coefficient of variation for the pH is higher on Alfisols and Planosols (11 and 10%, respectively) than on Vertisols (4%). The coefficient of variation for clay content is high on Planosols (58%), small on Vertisols (9%) and intermediate on Alfisols (29%) (figure 5.17).

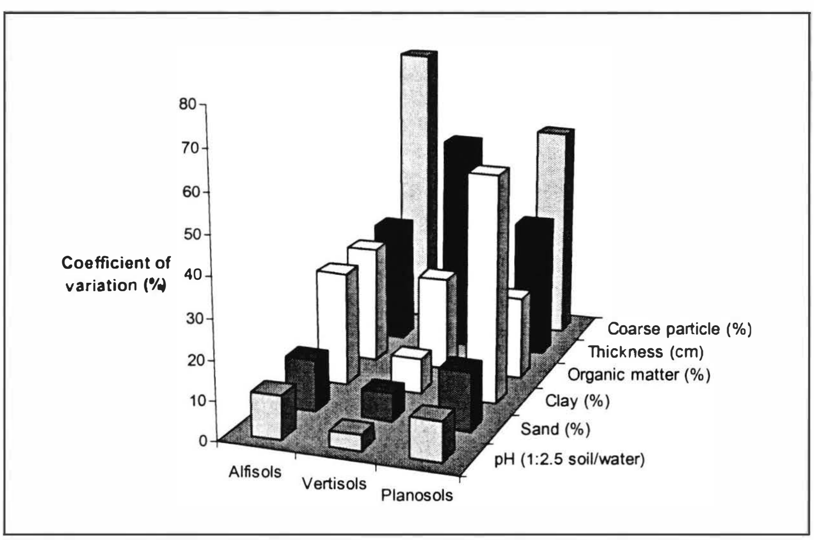


Figure 5.17 Variability of the properties between soil types within the severely eroded soil class

5.3.4 Conclusion

The values of the coefficient of variation for selected soil properties were compared to highlight the variability within erosion classes of a given soil (within map units), between erosion classes of a given soil (between map units), and within soil types. The degree of variability in soil properties changes considerably within and between erosion classes.

Within each erosion class of a given soil type, the general tendency is that thickness of the topsoil layer and coarse particle contents exhibit high variations, pH exhibits small variations, whereas organic matter and clay contents show intermediate variations. High and moderate variations can be attributed to differences in land use and soil management, whereas small variations can be attributed to parent materials. Differences in the degree of variation for soil properties imply different sensitivities of these properties to changes caused by erosion. Soil characteristics that are directly affected by land use and soil management vary significantly.

For many soil properties, the order of increasing degree of variation is indicated by slightly eroded soils < moderately eroded soils < severely eroded soils. Increased soil variability with increasing erosion severity suggests that erosion causes the soil properties to change in such a way that more erosion takes place. In fact, more eroded soils offer favorable conditions to substantial changes because interrelationships among soil properties are poor. In contrast, on Alfisols and Vertisols the order of increasing degree of variation for clay contents is indicated by more eroded soils < less eroded soils. Removal of the topsoil layer due to erosion is accompanied by the exposure of homogeneous clayey subsoil layers, minimizing the variations of the clay contents at the soil surface.

Variations within each erosion class of a given soil type are small compared to within the soil type as a whole. Erosion changes with increasing area, causing substantial variations in soil properties. Therefore, the subdivision of each soil type into erosion classes tends to reduce the variability of the soil properties within map units. Erosion classes generate relatively homogeneous units, allowing for the extrapolation of the point data obtained by rainfall simulation.

Considerable differences in the coefficients of variation for different soil properties within erosion classes suggest that the assessment of soil variability may require different numbers of samples for each property. Similarly, substantial differences in the coefficients of variation between erosion classes may require different sampling schemes in different erosion classes.

5.4 DISTRIBUTION PATTERNS OF SOIL TYPES AND EROSION CLASSES

5.4.1 Variability and distribution patterns of soil types

Variability that occurs between soil types appears to be mainly controlled by the parent material. For instance, the particle size may vary considerably due to differences in inherent properties of the parent materials. Geological materials such as granite and gneiss exhibit differences in mineralogical constitution. The occurrence of similar soils in different landscapes can be attributed to topography. For instance, despite differences in elevation, typical soil variations and distribution patterns on mountains and hills consist of rock outcrops and Entisols on the summits, small areas of Entisols on the backslopes, and relatively large areas of Inceptisols on colluvium at the footslopes. This distribution pattern can be attributed to similarity in topography, described as convex ridge summits, straight and hilly to very steep (more than 16% slope) backslopes and concave footslopes; this influences soil development. Similarly, the distribution of the Alfisols is related to the topography of the landscape rather than the elevation. Alfisols occur on nearly level to gently sloping (0 to 3% slope) mesas in the plateau and on nearly level to gently sloping glacis-terraces in the plain. The elevations range from 800 to 850 m and from 510 and 605 m for the plateau and plain, respectively.

High consistency in the segregation of map units is provided by the geopedologic approach and soil-landscape pattern analysis, which recognizes and uses relationships between soil properties and readily identifiable, permanent, unambiguous and closely related geomorphic units. A landform type, at the lower categorical level of the geoform classifcation system, represents a geomorphic unit that incorporates processes and systems of close interactions between physical (topography), physicochemical (soil) and managerial (human practice) factors, that regulate water movement and influence soil formation and erosion. In other words, relationships between environmental factors facilitate the prediction of soil distribution from a knowledge of terrain characteristics (Zinck, 1988).

5.4.2 Variability and distribution patterns of erosion classes

Variability that occurs between erosion classes seems to be mainly controlled by the combination of topography and past erosion, although the type of land use may also influence the distribution. Less eroded soils are on nearly level surfaces to gentle slopes, whereas more eroded soils are on undulating to very steep slopes For instance, less eroded Alfisols are on the treads of the glacis, whereas more eroded Alfisols are on the undulating risers of the glacis, in the plain. The slope ranges from 0 to 3% and from 3 to 8%, respectively. Eroded soil surfaces may change the hydrological conditions, promoting in return on-site erosion.

5.4.3 Homogeneity within map units

The relative homogeneity within map units can be caused by the relatively homogeneous topographic conditions. However, variations may occur due to local differences. For instance, clay and organic matter contents may vary due to local hydrological and slope conditions, which cause selective erosion. They may also vary due to differences in land use. For instance, variations in organic matter content can be due to differences in the density of the cattle excreta during grazing. Local disturbances, such as fire, tree fall, earth worm and termite activities, can generate high variation of soil properties at short distance, within map units.

5.5 CONCLUSION

This chapter reviews the major soil types and erosion classes in the Gawar area. There is a high variability in soil types, correlated with the variability of the geologic and geomorphic conditions. Soils were classified according to three systems, including CPCS (1967), Soil Taxonomy (USDA, 1996) and FAO (1998). In contrast to the other classification systems, the FAO soil classification differentiates Lixisols from Planosols, and Fluvisols from

Leptosols at the upper classification level. Farmers also make a clear distinction between Lixisols, Planosols, Leptosols and Fluvisols, and allocate these soils to specific land uses. As a result, only the FAO soil classification will be used regularly in the following chapters.

Within each soil type, erosion (or past erosion) has caused modifications that have affected the soil profiles. These modifications have created considerable variations of the soil properties within a given soil type. According to the degree of changes, three erosion classes were identified and described: slightly eroded soils, moderately eroded soils, and severely eroded soils. Considering the overall variation, soils defined on the basis of erosion classes provide map units that are more uniform in terms of their soil properties than the soil type as a whole. This indicates a high consistency of the geopedologic approach in segregating map units. Modifications of the soil properties due to erosion suggest that the different erosion classes of a given soil type should be allocated to different land uses. Similarly, the susceptibility of a soil type to erosion changes according to erosion classes.

CHAPTER 6

FARMING SYSTEMS AND SOIL EROSION

Individual interviews with 120 farmers and field observations allow to characterize farming systems at three levels: the regional level, the local level, and the farm level. At regional level, farming activities are described with respect to the environment in a global context. The study at local level deals with the allocation of the land according to the erosion classes of the major soil types. At farm level, daily operations to ensure crop production are analyzed. The indicators of soil erosion and main constraints to crop productions are discussed at each level. Additionally, a proposal for rehabilitating severely eroded soils is presented.

6.1 DEFINITION OF CONCEPTS

6.1.1 Farming system

A farming system is a system of agriculture or livestock, characterized by a customary pattern of behaviour which results in a typical allocation, management and development of resources as well as decisions and processes within a farm unit, in a given time. The types of resources are natural (land, water, vegetation), human and animal (labour). A farming unit is an entity (cultivated plot by agricultural farmers or used by pastoralists) concerned with agricultural or animal output commodities (De Schlippe, 1956; Krantz, 1974; Norman, 1979; Upton, 1987).

6.1.2 Subsistence farming

Subsistence farming is a system in which effort is directed toward producing food mostly for consumption and only very little amount, if any, is sold to purchase at the very minimum goods of the first necessity such as salt, kerosene, soap, medicals and clothes. It consists of six main characteristics: (1) high ratio of consumption to sale; (2) low ratio of hired labour input to total labour input; (3) low ratio of purchased factor inputs to total factor inputs; (4) low level of production technology; (5) low level of income; and (6) substantial influence of non-economic factors on decision-making (Wharton, 1969).

6.1.3 Shifting cultivation

Shifting cultivation is a system in which a cropping period alternates with a longer rest or fallow period during which the abandoned crop area is recolonized by natural vegetation to restore soil fertility. Morgan (1969) defined shifting cultivation as a rotation of fields rather than crops, by short periods of cropping alternating with long fallow periods. Wharton (1969), and Wolfgang and Cesar (1993) pointed out that shifting cultivation is viewed as:

- an itinerant agriculture: cultivators are less sedentary than farmers operating more intensive systems;
- a subsistence form of agriculture;
- land demanding, low yielding and labour intensive;
- an obstacle in the endeavor to improve the food supply in food-deficient countries.

Too short fallow periods are not restorative. The primary vegetation community cannot reestablish, and the subclimax is not effective in restoring soil organic matter content, fertility status and physical characteristics. Reed (1951) showed that under conservative shifting cultivation systems, the fertility levels of the primary vegetation community can take more than a century to reestablish itself. In western Africa, under a period of 2 year-crop and 10 year-fallow, soil organic matter content reestablished at about 75% of that of primary vegetation.

6.1.4 Types of agriculture and cropping pattern

Seven types of agriculture are identified. Morgan (1969), Wharton (1969), Ruthenberg (1971), Norman (1979) and Upton (1987) defined these as follows.

(1) Rainfed agriculture

Rainfed agriculture is a type of agriculture in which the crop is grown on natural rainfall during the rainy season.

(2) Post-rainy season agriculture

Post-rainy season agriculture is a type of agriculture in which the crop is grown on stored moisture during the period that follows the rainy season.

(3) Irrigated agriculture

Irrigated agriculture is a type of agriculture in which there is a practice of controlled supply of water to an area where crops are grown and where soil moisture is the limiting factor to plant growth.

(4) Intensive agriculture

Intensive agriculture is a continuous cropping on a land until adverse effects on yields are shown out. The duration of continuous cropping varies according to soil characteristics and agricultural practices. Intensive agriculture is practiced on fertile soils.

(5) Extensive agriculture

Extensive agriculture is a cropping pattern that, due to low productive capacity of the soil to cropping, increasing production requires an increase of the cropping area.

(6) Crop rotation

Crop rotation pattern is a practice in which crops with different characteristics are rotated or are alternated on the same piece of land.

(7) Cropping and tillage systems

Mixed cropping is a cropping system in which mixtures of crops with different characteristics (moisture requirements, rooting depth, sowing dates, harvesting dates) are done on a given land at a time, but not arranged in a geometric pattern. Intercropping pattern is a mixed cropping where crops on a given land at one time are arranged in a geometric pattern, for instance, two rows of sorghum alternating with two rows of groundnuts. The main advantages of these cropping patterns are as follows:

- the risk of pests and deseases reducing total food supply is minimized;
- the risk of intermittent adverse weather (drought spells) reducing total food supply is minimized;
- a diverse and nutritionally adequate diet is assured;
- labour input is spread over time.

No-tillage (zero tillage) is a tillage system whereby a crop is seeded directly into a seedbed that has not been tilled since the previous seedbed. Minimum tillage is the minimum soil manipulation necessary for crop production or meeting tillage requirements under the existing soil and climatic conditions (Resource Conservation Glossary, 1982).

6.1.5 Types of animal husbandry

(1) Stock composition

Based on the stock composition, four types of animal husbandry can be distinguished: large livestock, small livestock, transport and traction animals, and poultry.

(a) Large livestock

A large livestock consists of managing cattle. Every morning, herds of 50 to 100 animals are taken away to graze on fallow land, on fields after harvesting and on uncultivated areas. In the evening, the herds are taken back to compounds or to corrals, where animals may obtain additional fodder from the crop residues.

(b) Small livestock

A small livestock concerns sheep and goats. Herds of animals may graze together with the cattle as long as the distance to pastures is less than approximately 5 km. Most often, the animals graze on fallow and on uncultivated lands nearby the village. Supplementary feeding from the crop residues is provided.

(c) Transport and traction animals

Animals used for transportation and traction include donkeys and pairs of oxen. Horses are only kept for sport (races) and ceremonial occasions. They graze mainly on crop residues and receive better care.

(d) Poultry

The poultry is composed of chicken, ducks and guinea fowls. These birds are kept around the compounds. They feed on grains, household refuses and termites collected from the fields. Sometimes, they are taken to fields where they feed on insects.

(2) Stock management

Based on the composition of the fodder and distance to grazing areas, two types of livestock system can be distinguished: intensive livestock and extensive livestock.

(a) Intensive livestock system

Intensive and sedentary livestock is a system in which stall feeding is practiced. Animals receive on the spot stubble and trash brought from the fields. The animal can graze on fallow land and on uncultivated areas nearby house compounds. The herds are composed of goats, sheep, and donkeys and pairs of oxen used for labor (transportation, traction). Non-ruminant animals, such as chickens, ducks and guinea fowls, are included.

(b) Extensive livestock system

Extensive livestock is a system in which flocks of animals graze on uncultivated areas, on fallow land, and on crop residues after harvesting. The type of animals (mainly cattle) and size of the herds (50 to 100 animals) imply that optimal amounts of fodder are reached by increasing the grazing areas. In fact, two variants of extensive livestock system exist: transhumant pastoralism and nomadic pastoralism. Transhumant pastoralism is a system in which herds that are resident in one area are moved to another for a short time in search for fodder. Nomadic pastoralism is a system in which seasonal migration of the herds occurs over long distances along periodical paths.

6.2 FARMING SYSTEMS AT REGIONAL LEVEL

6.2.1 The farmers' objectives

In general, farmers have two orders of objectives. The first order of the farmers' objective is subsistence, which means harvesting enough crops to secure an adequate and assured food supply until the next harvesting season. The second order of the farmers' objective includes buying cattle, schooling of their kids, payment of the government tax, medicines and clothes (table 6.1).

Table 6.1 Farmers' objectives in the Gawar area

Farmers' objectives	Farmers' response (%)
Subsistence	98
Buying cattle	85
Schooling of their kids	95
Payment of the government tax	90
Buying clothes, medicines	80

The farmers pointed out that the second order of objectives can only be reached if the resources remain, since they always have to face a hunger period (the period that preceeds the harvesting). During that period, the farmers can no longer sell any food because stocks are exhausted even for feeding themselves. Therefore, the objective of the farmers in the Gawar area mainly aims at survival in an uncertain environment.

6.2.2 The farmers' environment

(1) Seasons

There are three distinct seasons in the Gawar area: (1) a wet season, from June to September; (2) a cool and dry season, from October to December; and (3) a hot and dry season, from January to May. The average annual rainfall ranges from 900 to 1000 mm occurring within three months only, with potential evapotranspiration exceeding rainfall. Rainfall is extremely variable over time and space. The area has experienced many intermittent dry and wet spells.

(2) Soils

Soils are varied. The farmers' soil classification is based on the characteristics of the topsoil layers, including thickness, colour, stoniness, texture, and presence of cracks. Other aspects such as the type of vegetation, topography and external drainage are also taken into account. Soils are allocated to land uses, accordingly. Based on these characteristics, the farmers' nomenclature of soils approximately consists of six major soil types, approximately corresponding to Lixisols, Vertisols, Leptosols, Fluvisols, Planosols and Cambisols. The name of a soil varies according to the ethnic group to which the farmers belong. Therefore, only the soil names from the major ethnic group called, "Foulbé", are used.

The farmers' name for Lixisols included "Sabéré" and "Lesdi". The topsoil layers of "Sabéré" are dark brown (10YR 3/3, dry) to yellowish brown (10YR 5/4, dry), 15 to 30 cm thick, with massive primary structure breaking into single-grained secondary structure, sandy loam to loamy sand texture. The name "Sabéré" stems from groundnut because these soils are suitable to groundnut cultivation. They are devoted to rainfed agriculture. Major crops are sorghum, millet, groundnuts and cotton. "Sabéré" soils are highly susceptible to erosion and highly sensitive to dry spells. When erosion occurs, the red to yellow subsoil layers outcrop at the soil surface; "Sabéré" are then transformed into "Lesdi", meaning red soil, in the local dialect.

The local soil name "Boulwol" or "Lopé" refers to Vertisols in the FAO soil classification. The farmers recognize "Boulwol" from the dark gray colour (5Y 4/1, dry), very clayey texture, presence of large cracks in the dry season, presence of free water at the soil surface in the rainy season, and *Acacia* vegetation type. "Boulwol" are very fertile soils and are specially allocated to post-rainy season cultivation of dry sorghum (Mouskwari sorghum). A "Boulwol" plot cultivated with Mouskwari sorghum is called "Karal". The limited extension of Boulwol does not match the high human and animal populations in the Gawar area.

"Kourkaye" soils correspond to Leptosols in the FAO soil classification. In fact, "Kourkaye" in the local dialect means soils that show a high concentration of rock fragments at the soil surface and in the soil profile, and that present fast disposal of rain water at the soil surface. "Kourkaye" are generally found on steep slopes of highlands and on erosional glacis. Eroded Lixisols that present a high concentration of rock fragments are called "Kourkaye Lesdi", meaning red soils with high concentrations of rock fragments. The main constraints of "Kourkaye" to crop production are: shallow rooting depth, excessively rapid external drainage, small capacity of moisture storage, high sensitivity to dry spells, and high susceptibility to erosion. Despite these constraints, "Kourkaye" are devoted to intensive rainfed agriculture, probably because they have a high cation exchange capacity and a high base saturation.

Fluvisols are reflected in a variety of local names, including "Dandé Mayo", "Roufri Lougéré Maroga" or "Yoldé". Generally speaking, these names mean alluvium deposits. The variations in the local soil names correspond to the nature of the sediment: sand, silt or loam. Irrigated vegetables are increasingly cultivated on these soils in the Gawar area.

Planosols refer to "Hardé" in the farmers' nomenclature of soils. The farmers recognize "Hardé" from their high sensitivity to dry spells and their high susceptibility to erosion. "Hardé" have massive, hard, compact and impervious clayey subsoil horizons, which promote runoff and enhance erosion. The implications for agriculture are poor hydrological properties that restrict water infiltration, shallow rooting depth, small capacity of moisture storage, and high hardness that makes pre-plant operations difficult and almost impossible by traditional methods. "Hardé" have a crusted surface, which leads to runoff production and soil erosion. In fact, "Hardé" means sterile soil in the local dialect. However, any soil that has acquired the above properties by degradation, such as hardening and erosion (occurrence of the hard and clayey subsoil layers at the surface), or land use (soil compaction), is also called "Hardé". Thus, "Hardé Boulwol" means sterile soil originated from degradation of Vertisols.

Cambisols do not have a specific correspondence in the local soil nomenclature. Cambisols may pertain to different soil types in the local soil classification, because the farmers emphasize the characteristics of the topsoil layers.

(3) Water

The main sources of water are rainfall and groundwater. A long-term decline of rainfall, associated with a high potential evapotranspiration, is causing the depletion of the groundwater table even along the rivers. This results in drying wells, which enhances the problems of drinkable water and vegetation growth.

6.2.3 Human activities

In the Gawar area, crop production is associated with livestock. Based on the intensity of the practices, two groups of farmers are distinguished. The first group consists of agriculture-livestock farmers in which agriculture is more important than animal husbandry. The second group consists of livestock-agriculture farmers in which more activities deal with animal husbandry than with crop production. Integration of these activities is complex and their interactions are many. Nevertheless, integrating human activities, seasons and soils permit to distinguish five majors farming systems as presented in table 6.2.

Table 6.2 Farming systems at watershed level

Farming systems	Activities	Seasons	Soil types
1	Rainfed agriculture Extensive livestock	Rainy season Hot dry season	Cambisols, Fluvisols, Leptosols Lixisols, Planosols
2	Irrigated agriculture Extensive livestock	Cool dry seaon Hot dry season	Fluvisols, Cambisols (developed on alluvium)
3	Rainfed agriculture Intensive livestock	Rainy season All year long	Cambisols, Fluvisols, Leptosols Lixisols, Planosols
4	Post-rainy season agriculture Extensive livestock	Cool dry season Hot dry season	Vertisols
5	Extensive livestock Fuelwood harvesting	All year long All year long	Cambisols, Fluvisols, Leptosols Lixisols, Planosols, Vertisols

(1) Agricultural activities

(a) Rainfed agriculture

Rainfed agriculture is practiced on all soil types, except Vertisols and Fluvisols. The cropping season goes from April - May (land clearing) to September - October (harvesting). Major crops are sorghum, millet, maize, cowpea and groundnuts. Cotton is the only cash crop encountered. Minor crops are fonio, sesame, elusine and several legumes.

(b) Irrigated agriculture

Irrigated agriculture is practiced for market in gardens on Fluvisols. The growing season stretches from October to February. Major crops are onion, cabbage, salad, tomato and carrot.

(c) Post-rainy season agriculture

Post-rainy season agriculture concerns the cultivation of the dry sorghum (Sorghum bicolor L.), also called Mouskwari in the local dialect. The crop is cultivated exclusively on Vertisols and other soils with pronounced vertic properties. Post-rainy season agriculture has been possible due to the combined effect of the soil properties and crop characteristics, as detailed in the following section.

(2) Importance of the post-rainy season cropping of Mouskwari sorghum on Vertisols

(a) Coverage and use

Vertisols have been considered as rather marginal for arable cropping because they are difficult to manage. They are hard and cloddy when dry, and very sticky when wet. As a consequence, they remain underutilized (Willcocks and Browning, 1986; Asnakew Woldeab, 1987; Walsh, 1987).

The Vertisols cover worldwide about 280 million hectares, located mainly in Africa, Australia, India and the USA. More than 126 million hectares are found in Africa, where resources and facilities are limited and food shortage is common (Asnakew Woldeab, 1987). Vertisols and associated clayey soils cover about 1.2 million hectares, representing 12% of the semiarid zone in northern Cameroon (Ambassa et al., 1996; Brabant, 1987). They remain fallow during the rainy season, from May to September, and are cropped with sorghum (Mouskwari sorghum) during the post-rainy season, from September to February. The cultivation of the dry sorghum is possible due to the combined effect of the soil properties and crop characteristics.

(b) Characteristics of the Vertisols

On Vertisols, the presence of cracks delays the wetting of the surface horizons, which prevents the crop to establish. At the beginning of the rainy season, runoff rapidly moves into the cracks and wets the deeper layers of the soil, while the surface horizons remain relatively dry. The subsurface horizons, below the zone of cracks, are moistened first. As the rainy season proceeds, soil moisture increases from the bottom to the top of the soil profile, associated with the closing of cracks. Maximum water storage in the profile is reached at the end of the rainy season. Stored water is enough to grow the Mouskwari sorghum during the period that follows the rainy season. Available water is estimated to be 110 to 250 mm for the upper meter. At the end of the rainy season, the moisture content in the topsoil layers is higher than the moisture content in the subsoil layers (Virmani et al., 1982; Seiny, 1990).

Michaels (1981) reported that the rainy season fallows, during which Vertisols may not permit any cropping, can be separated into two phases. The first phase represents dry fallows, in which the rainfall during the rainy season is unreliable and bare fallowing is essential to accumulate sufficient water in the profile to grow a crop on stored water in the post-rainy season. The second phase represents wet fallows, in which the rainfall during the rainy season is adequate to excessive. Cropping during that period faces high risks of losses from waterlogging and flooding.

(c) Characteristics of the Mouskwari sorghum

The high water-holding capacity of the Vertisols allows to compensate moisture availability better than other soils for the low and erratic rainfall (Swindale, 1987). The capability of the Mouskwari sorghum to grow on stored water, without receiving any additional rain, and to use soil moisture even at a pressure of 18 bars (Obale et al., 1993) ensures extra yields. Farmers point out that fields of Mouskwari sorghum that receive any rain are generally subjected to crop failure. Additionally, they sustain that Vertisols are the most potential soils for productive cropping. Farmers don't feel safe without any acreage of Vertisols for the post-rainy season cropping. The annual consumption of Mouskwari sorghum by an average family in the semiarid zone of Cameroon is 1750 kg (Djonnewa, 1996). It is about 800 kg for rainfed sorghum, maize, cowpea and groundnuts.

(3) Animal husbandry

Animal husbandry is an integrated crop-animal husbandry farming system, based on alternating periods of cropping during plant growth season with periods of grazing during post-harvesting season. Over a year, there is a shift from transhumant pastoralism to nomadic pastoralism, covering four periods:

- The first period corresponds to the cropping season and goes from June to October. In the morning time, the animals are taken to uncultivated lands where they graze on vegetation species such as *Pennisetum pedicellatum, Staria punita, Thelepogon elegans, Alysicarpus olalifolius* and *Aristida hordeacea*. In the afternoon, the animals are taken back to the village where they spend the night in the fences or corrals.
- The second period goes from November to December during which the animals feed on stubble and trash remained on fields, after harvesting. Grazing on previously uncultivated lands continues.
- The third period goes from January to March. Feeding on stubble continues. However, the very limited amount of stubble forces animals to go in search for new grazing lands. The distance to grazing areas increases. The herders and their animals may spend some nights in the brush. Exhausted grazing lands are put on fire to stimulate vegetation regrowth. The herders remove the bark and young branches of some tree species (*Ficus spp, Khaya senegalensis* and *Tamarindus indica*) to feed the animals.
- The last period goes from April to June. It is characterized by the lack of vegetation and water. The animals are taken to remote areas, about 50 to 70 km to the south, where there is relatively less pressure on the land due to lower population density. The animals remain there till the beginning of the rainy season in June.

(4) Other activities

Another activity (but not the least one) is fuelwood harvesting. Firewood is the main source of energy. The farmers cut the trees not only for their own fuel needs, but also sell them to satisfy the demand from the surrounding main cities (Maroua and Mokolo). The farmers argue that they cannot avoid selling firewood, because it is the only source of income, when their food stocks are exhausted and they want to make money to satisfy their needs (medicines, schooling their kids). Minor activities include hunting and insect harvesting to feed chickens.

6.2.4 Constraints to crop and animal productions at regional level

Four main factors constraint crop production at regional level: (1) pronounced drought, (2) drying of rivers and springs, (3) soil fertility depletion and erosion, and (4) lack of fodder for feeding animals.

(1) Pronounced drought

Pronounced drought is considered by farmers as being the most limiting factor to crop production in the Gawar area. Prolonged dry spells within the rainy season cause soil moisture stress, which affects plant growth and decreases yields. Additionally, heavy rains at the end of the rainy season may damage the farm products at mature state. Regularly distributed and gentle rains are needed for successful rainfed crop productions.

On Vertisols, however, gentle rains accompanied by high evapotranspiration may not allow cracks to absorb sufficient water. Maximum water storage is satisfied under heavy rains, which increase moisture contents for plant growth during the post-rainy season.

(2) Drying of rivers and wells

Drying of rivers and springs causes the farmers to face the problems of drinkable water for human and animal populations, and irrigation water for vegetation growth.

(3) Soil fertility depletion/erosion

According to farmers, soil fertility decreases in the following order: Vertisols > Leptosols > Fluvisols > Cambisols > Lixisols > Planosols. The high susceptibility of the soils to overland flow causes soil erosion, associated with loss of nutrients, soil moisture depletion and yield decrease. The order of increasing susceptibility of soils to erosion as indicated by the farmers is Vertisols < Cambisols < Lixisols < Planosols < Leptosols.

(4) Lack of fodder for animal feeding

Animal husbandry substantially contributes to farmers' income in the Gawar area. Many farmers report death of more than 50% of their animals because of the lack of fodder during the dry season, a fact which decreases farmers' revenue and enhances poverty.

6.3 FARMING SYSTEMS AT LOCAL LEVEL

6.3.1 Typology of the farming systems

The typology of the farming systems in the Gawar area is based on the relationships between the land uses and the erosion classes of the major soil types. The main characteristics controlling classification of the farming systems are loss of agricultural specialization and reduced land use diversity with increasing erosion severity (table 6.3).

Table 6.3 Farming systems and erosion classes of the major soil types

Soil types	Erosion classes		
	Slightly eroded	**Moderately eroded**	**Severely eroded**
Leptosols/Cambisols (highlands)	Intensive terrace agriculture Intensive livestock	Extensive rainfed agriculture Extensive livestock	Extensive livestock Extensive fuel wood harvesting
Cambisols/Lixisols/ Planosols (lowlands)	Intensive rainfed agriculture Extensive livestock	Extensive rainfed agriculture Extensive livestock	Extensive livestock Extensive fuel wood harvesting
Vertisols (lowlands)	Intensive Mouskwari cropping Extensive livestock	Intensive rainfed agriculture Extensive Mouskwari cropping Extensive livestock	Extensive livestock Extensive fuel wood harvesting
Fluvisols/Cambisols (river banks)	Intensive irrigated agriculture Extensive livestock	Extensive rainfed agriculture Extensive livestock	Extensive livestock Extensive fuel wood harvesting

Spatial distribution of the farming systems in relation to erosion classes is presented in figure 6.1 and table 6.4.

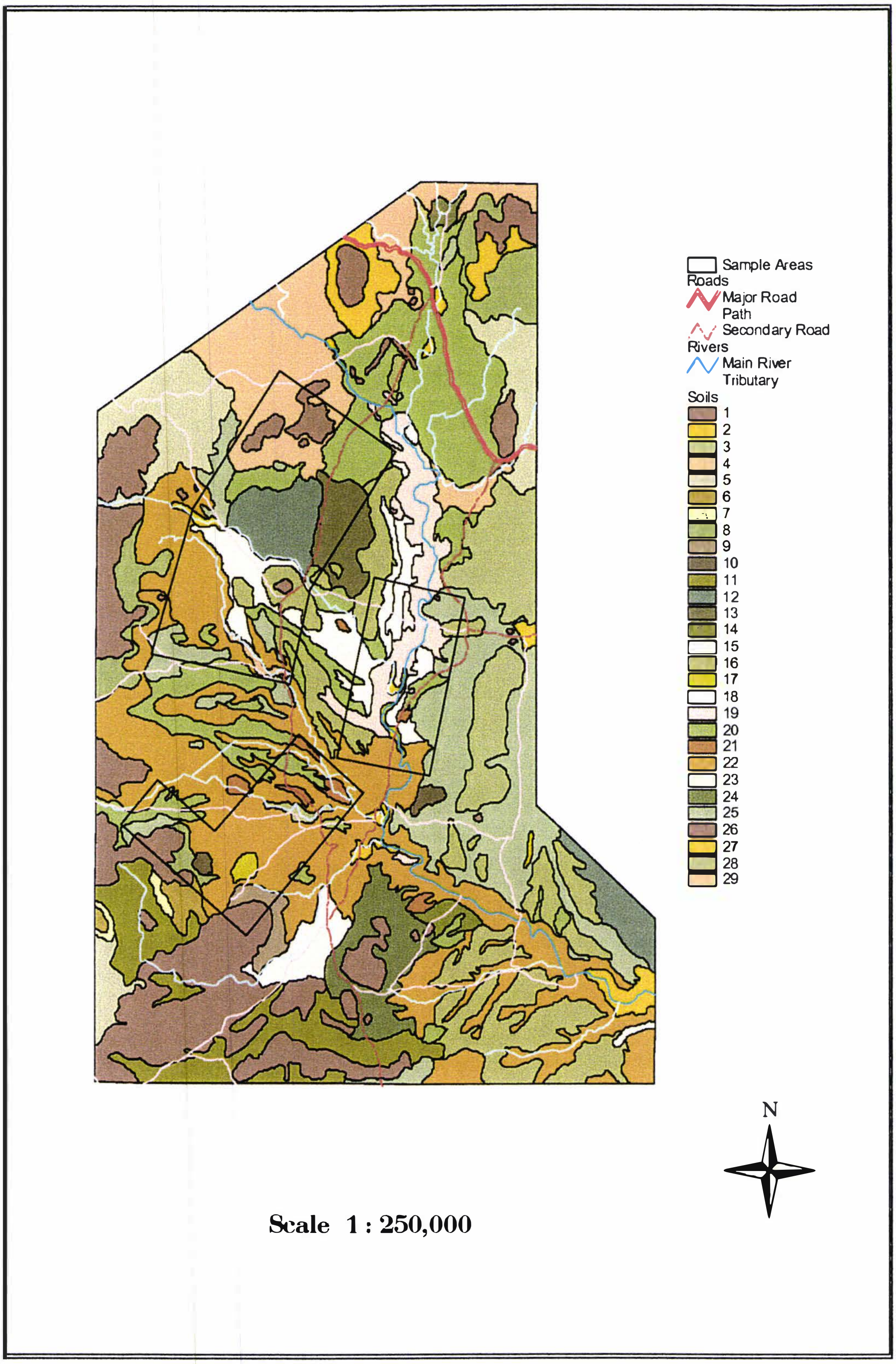


Figure 6.1 Distribution of the farming systems at local level

Table 6.4 Legend of the distribution of the farming systems at local level (figure 6.1)

Landscape	Relief/Molding	Altitude (m)	Lithology	Landform	Map unit type	Slope (%)	Soil types (FAO, 1998)	Farming systems	Soil management	Erosion class	Area (ha)	MU
Mountain	Ridges	700 - 1060	Granite, migmatite, anatexite, quartzite, basalt	Slope-facet complex	Association	15 - 60	Lithic Leptosols Rock outcrops	Extensive livestock, fuelwood harvesting		Excessive	10230	1
				Footslope	Consociation	12 - 20	Eutric Cambisols	Intensive rainfed agriculture, intensive livestock	Stone wall terraces	Slight	1215	2
Hilland	Ridges	700 - 965	Granite	Slope-facet complex	Association	33 - 43	Lithic Leptosols Rock outcrops	Extensive livestock, fuelwood harvesting		Excessive	3345	3
Plateau	Hills in "half-orange"	700 - 900	Granite, migmatite, anatexite	Slope-facet complex	Association	8 - 9	Eutric Cambisols Lithic Leptosols	Intensive rainfed agriculture, intensive livestock	Stone wall terraces	Slight	5620	4
					Association	19 - 23	Lithic Leptosols Rock outcrops	Extensive livestock, fuelwood harvesting		Severe	3659	5
	Mesas	800 - 850	Gneiss, embrechite	Tread	Consociation	0 - 1	Haplic Lixisols	Intensive rainfed agriculture, extensive livestock	Ridge-furrow system (*)	Slight	386	6
	Escarpments	600 - 800	Gneiss, embrechite (pediment)	Scarp-talus complex		24 - 40	Eutric Cambisols Lithic Leptosols	Extensive livestock, fuelwood harvesting		Severe	182	7
Piedmont	High glacis	580 - 600	Colluvium	Erosional glacis	Consociation	11 - 15	Lithic Leptosols	Extensive livestock, fuelwood harvesting		Severe	2261	8
	Low glacis	560 - 580	Colluvium	Erosional glacis	Consociation	5 - 8	Haplic Lixisols	Shifting rainfed agriculture, extensivelivestock	Ridge-furrow system (*)	Moderate	458	9
	Hills	700 - 900	Granite, anatexite	Slope-facet complex	Association	20 - 40	Lithic Leptosols Rock outcrops	Extensive livestock, fuelwood harvesting		Excessive	212	10
Peneplain	Hills in "Half-orange"	600 - 650	Granite, migmatite, anatexite, gneiss	Slope-facet complex	Association	4 - 6	Haplic Lixisols Vertic Cambisols	Shifting rainfed agriculture, extensivelivestock	Ridge-furrow system (*)	Moderate	3871	11
				Slope-facet complex	Association	4 - 8	Lithic Leptosols Haplic Cambisols	Extensive livestock, fuelwood harvesting		Severe	2256	12

Remark: (*): The ridge-furrow system is done along the slope

Table 6.4 (continuation)

Landscape	Relief/Molding	Altitude (m)	Lithology	Landform	Map unit type	Slope (%)	Soil types (FAO, 1998)	Farming systems	Soil management	Erosion class	Area (ha)	MU
Plain	High erosion glacis	590 - 605	Migmatite, quartzite	Tread-riser complex	Consociation	2 - 6	Haplic Lixisols	Shifting rainfed agriculture, extensivelivestock	Ridge-furrow system (*)	Moderate	1186	13
					Association	3 - 8	Vertic Cambisols Chromic Lixisols Haplic Planosols	Extensive livestock, fuelwood harvesting		Severe	299	14
	Middle erosion glacis	560 - 590	Gneiss, quartzite	Tread	Consociation	0 - 1	Haplic Lixisols	Intensive rainfed agriculture, extensivelivestock	Ridge-furrow system (*)	Slight	1919	15
			Embrechite	Tread	Consociation	0 - 1	Eutric Vertisols	Intensive post-rainy season cultivation, extensive livestock		Slight	6949	16
				Riser	Consociation	1 - 2	Vertic Cambisols	Intensive post-rainy season cultivation, extensive livestock		Slight	132	17
	Low erosion glacis	510 - 560	Gneiss, quartzite	Tread	Consociation	2 - 4	Haplic Lixisols	Shifting rainfed agriculture, extensive livestock	Ridge-furrow system (*)	Moderate	1825	18
				Riser	Consociation	2 - 6	Chromic Lixisols	Extensive livestock, fuelwood harvesting		Severe	2345	19
			Embrechite	Tread	Consociation	2 - 4	Haplic Vertisols	Intensive rainfed agriculture, shifting post-rainy season cultivation, extensive livestock	Ridge-furrow system (*)	Moderate	10260	20
				Riser	Consociation	3 - 5	Haplic Vertisols	Extensive livestock, fuelwood harvesting		Severe	460	21
					Consociation	3 - 10	Vertic Cambisols	Shifting rainfed agriculture, extensive livestock	Ridge-furrow system (*)	Moderate	16569	22
			Gneiss, migmatite	Tread	Consociation	2 - 3	Haplic Planosols	Intensive rainfed agriculture, extensivelivestock	Ridge-furrow system (*)	Slight	74	23
				Riser	Consociation	2 - 13	Haplic Planosols	Shifting rainfed agriculture, extensive livestock	Ridge-furrow system (*)	Moderate	2071	24
					Consociation	2 - 5	Haplic Planosols	Extensive livestock, fuelwood harvesting		Severe	7851	25
	Inselberg	600 - 800	Granite, quarzite, basalt	Slope-facet complex	Association	40 - 60	Lithic Leptosols Rock outcrops	Extensive livestock, fuelwood harvesting		Excessive	418	26
Valley	Floodplain	510 - 580	Recent alluvium	Tread	Consociation	0 - 1	Haplic Fluvisols	Intensive irrigated agriculture, extensive livestock	Broad bed	Slight	1147	27
					Consociation	0 - 1	Haplic Fluvisols	Intensive irrigated agriculture, extensive livestock	Broad bed	Moderate	144	28
	Terrace	550 - 580	Ancient alluvium	Tread	Consociation	3 - 4	Fluvic Cambisols	Shifting rainfed agriculture, extensive livestock		Moderate	579	29

Remark: (*): The ridge-furrow system is done along the slope

(1) Farming systems on slightly eroded soils

Slightly eroded soils consist of good agricultural land that has been cultivated for more than a century, or newly incorporated agricultural land taken from formerly protected areas. This land is also used for grazing (straw) after harvesting. Potential use is almost the same as on uneroded soils. Only slight modifications of management are required to maintain crop production. Slightly eroded soils allow a high diversity of land uses. Four types of farming system were identified, including: (1) intensive terrace agriculture associated with intensive livestock; (2) intensive rainfed agriculture associated with extensive livestock; (3) intensive Mouskwari sorghum cultivation associated with extensive livestock; and (4) intensive irrigated agriculture associated with extensive livestock.

(a) Intensive terrace agriculture associated with intensive livestock

Intensive terrace agriculture associated with intensive livestock is a specialized production system in highlands, which has been used for centuries. It is a small-scale agriculture, practiced by poor farmers. Stone wall terraces have been constructed, which are exposed to breakage after heavy rainstorms or after the passage of roaming herds. Damaged terraces are repaired regularly. Rainfed agriculture consists of cropping sorghum, millet, cowpea and groundnuts in intercropping or mixed cropping pattern, and sweet potatoes and cotton in a single cropping pattern. These crops are supplemented by vegetables, grown in home gardens. Because it is less drought-resistant than sorghum and millet, maize is also grown in home gardens where it benefits from domestic waste water. Soil fertility is maintained by incorporating household refuse and animal manure. Intensive livestock is conducted around house compounds where goats, sheep, chickens, ducks, and guinea fowls are kept.

(b) Intensive rainfed agriculture associated with extensive livestock

Intensive rainfed agriculture associated with extensive livestock is found on Lixisols, Cambisols and Planosols. It concerns cropping of sorghum, millet, maize, cowpea and groundnuts. Minor crops such as sesame and fonio are common. Cotton is the only cash crop and is produced as a single crop. The cropping pattern is a rotation of crops. Three main rotation sequences are found: (1) cotton/cereals/groundnuts, (2) cotton/cereals/legumes, and (3) cotton/cereals/cassava. The staple crops are sorghum and millet. Although the staple crops receive the highest priority for land allocation, they always come after cotton in the rotation sequence to benefit from the effect of chemicals applied during cotton cultivation. The farmers reported that they cannot afford buying chemicals every cropping season. The National Coorporation for Cotton Development (SODECOTON) provides fertilizers on credit and buys the production from the farmers. After harvesting, flocks of animals graze on the stubble.

(c) Intensive Mouskwari sorghum cultivation associated with extensive livestock

Intensive Mouskwari sorghum cultivation is undertaken as a single crop on slightly eroded Vertisols, just after the rainy season. This type of farming system does not require fertilizers and weeds represent a relatively minor problem. After harvesting, animals feed on the crop residues remained on the field.

(d) Intensive irrigated agriculture associated with extensive livestock

Intensive irrigated agriculture associated with extensive livestock is practiced along the banks of the major rivers, where alluvium is deposited during the rainy season. Water is supplied by motopumping from the riverbed or wells. A nursery is constructed for the selection of plants. Production is sold on the market in the nearby cities (Mokolo and Maroua) and consists of onion, tomato, cabbage, salad and carrot. Local vegetables are also grown for family consumption. After harvesting, the fields are used as pastures where the animals graze on crop residues.

(2) Farming systems on moderately eroded soils

Moderately eroded soils include old agricultural lands of reduced soil fertility, that have been cultivated for more than a century. Erosion has changed the soil enough to require major improvements in soil and water conservation measures. Severely eroded grazing areas where the sward has been grazed and trampled are common. Two main farming systems were identified: (1) extensive rainfed agriculture associated with extensive livestock; and (2) intensive rainfed agriculture, together with extensive post-rainy season cultivation of Mouskwari sorghum, associated with extensive transhumant livestock.

(a) Extensive rainfed agriculture associated with extensive livestock

Extensive rainfed agriculture associated with extensive livestock is common on moderately eroded soils. Fallow is practiced to restore the soil fertility. But the fallow duration decreases because of population pressure. As a consequence, sorghum is being replaced by millet, that is better adapted to poor soils, but produces low yields. Extensive livestock activities are increasingly taking place here.

(b) Intensive rainfed agriculture, extensive post-rainy season cultivation of Mouskwari sorghum, associated with extensive livestock

The modifications of the soil properties, that occur in the surface horizon of the Vertisols due to erosion, impose changes in the cropping systems. Eroded Vertisols are characterized by their shallow depth, reduced cracks (size and number) and low shrink-swell potential. This results in insufficient water storage to support Mouskwari growth after the rains have ceased. Therefore, moderately eroded Vertisols are devoted to rainfed agriculture. Mouskwari sorghum is only sporadically cultivated on previous fallow areas, especially when yields from the rainfed agriculture are very low. Extensive livestock activities are undertaken after harvesting.

(3) Farming systems on severely eroded soils

Severely eroded soils have developed on old rangeland, where the sward has been heavily grazed and trampled for long periods, commonly more than 20 years. The productivity and land use diversity are considerably reduced. Erosion has changed the soils so much that the eroded soils are suited only for extensive cropping, grazing and firewood harvesting. Many areas are devoid of vegetation, with exposed subsoil layers and surface sealing. The main activities consist of extensive livestock, extensive fuelwood harvesting, and sporadic rainfed agriculture.

6.3.2 Constraints to crop and animal productions at local level

On less eroded soils, crop fields, crop specialization and cropping patterns are strongly correlated with the soil types. There is an equilibrium between arable land, grazing land,

and human and animal populations. But as the available arable land decreases with increasing populations and soil erosion, the soil-plant-water system is becoming unstable.

Five main constraints to crop and animal productions at local level were identified: (1) scarcity of arable land; (2) drying of wells and water ponds; (3) scarcity of forest and grazing areas; (4) scarcity of termite hills; and (5) pronounced hunger periods.

(1) Scarcity of arable land

Most fertile and less eroded soils are already being farmed so that the agricultural frontier expands on eroded, marginal and sterile soils. The scarcity of arable lands enhances land use conflicts between agricultural farmers and pastoralists.

(2) Drying of wells and water ponds

Although farmers commonly relate the drying of wells and water ponds to pronounced drought, they also recognize that soil erosion reduces groundwater recharge, which decreases the supply of water from the wells.

(3) Scarcity of forest and grazing areas

The extension of badlands due to soil erosion causes shrinkage of the forest areas, which reduces the supply of firewood and construction materials. Additionally, trees used for shading farmers, pastoralists and animals during hot spells, are decreasing. Cattle graze on natural pastures and crop stubble of low density, thus unable to provide adequate and sustainable supply.

(4) Scarcity of termite hills

Farmers feed most of their poultry with termites and insects. The scarcity of termite hills due to increased soil erosion is a constraint to chicken production in the Gawar area.

(5) Pronounced hunger periods

Although the annual rainfall seems suitable for growing a wide range of crops and for obtaining high yields, the farmers still produce at subsistence level. For instance, the average annual consumption of Mouskwari sorghum and rainfed sorghum per family is 1750 and 800 kg, respectively, whereas the annual production per average farm is only 200 and 350 kg (NCRE, 1994; Djonnewa, 1996). As a consequence, the farmers face a problem of unmatched proportions of crop production and food requirements for human and animal populations, which enhances the periods of hunger between two consecutive cropping seasons.

6.4 FARMING SYSTEMS AT FARM LEVEL

6.4.1 Main characteristics of agricultural production systems

In general, agricultural production systems in the Gawar area display the following characteristics:

- small scale subsistence-based farming, with average farm size of ¼ ha;
- slash-and-burn clearance technique is used;
- labour is mainly manual, using simple tools, such as hoes and machetes; use of livestock for transportation and draft is common;
- degrading agricultural practices (e.g. ploughing and ridge-furrow system down the slope) are common;
- soil fertility maintenance depends on manure, household refuse, and nutrient restoration during fallow periods;
- use of chemical inputs is very limited and concerns only cotton production;
- crop production is associated with animal production;
- yields are usually low (table 6.5).

Table 6.5 Average crop yields

Crops	Yields (kg ha^{-1})
Sorghum	700 - 2000
Muskwari	600 - 800
Millet	500 - 1100
Maize	600 - 1000
Cowpea	400 - 1700
Groundnut	600 - 1300
Cotton	500 - 1300

Source: NCRE (1994)

The staple food consists of sorghum and millet. Grain meals are often supplemented or substituted by starchy food, such as sweet potatoes and cassava.

6.4.2 Management practices

The farmers are aware that proper agricultural practices improve soil moisture content and reduce runoff and soil erosion. They actually use many agricultural practices to curb erosion and assure better yields. Farm management depends on many factors, including land suitability, the availability of agricultural tools, technical knowledge and economic resources.

The farmers recognize soil erosion indicators, including the following ones:

- Decoloration of the soil surface: erosion changes the colour of the soil surface horizons from darker to lighter or redder colours, because of the outcropping of subsurface horizons at the terrain surface.
- Accumulation of coarse materials on the soil surface because of selective erosion or sediment deposition through overland flow. Rills and shallow gullies form during heavy rains.
- Other features, such as increased compaction, spots of bare soil on cultivated areas, sprawling of weeds and decrease in yields, are considered as incidental soil erosion indicators.

Farming includes a set of mechanical, biological and chemical practices, which requires full dedication of the farmer all over the year, especially for rainfed agriculture (table 6.6).

Table 6.6 Calendar of agricultural activities

Period	Farming activities		
	Rainfed agriculture	**Irrigated agriculture**	**Post-rainy season sorghum cultivation**
April – May	Land clearing Seedbed preparation		
May – June	Sowing (sorghum + millet)		
June – July	Ploughing (cotton) Sowing (cotton, cowpea, legumes)		
July – August	Late sowing Weeding Chemical applications (cotton)		Nursery planting
August September	Weeding		
September October	Harvesting (food crops)	Nursery planting	Land clearing
October November	Harvesting (food crops)	Land clearing Seedbed preparation	Seedbed preparation Transplanting
December January	Harvesting (cotton)	Transplanting	Weeding
January - March	Harvesting (cotton)	Harvesting	Harvesting

(1) Mechanical practices

Mechanical protection measures concern all the methods that involve earth moving. Their objective is to modify the soil slope and to contain or control runoff (absorb, store or divert runoff). These measures include stone wall terraces, ridge-furrow systems and broad beds (table 6.7).

Table 6.7 Implementation of mechanical practices

Soil types	Mechanical measures	Farmers response(%)
Leptosols/Cambisols (highlands)	Terraces (stone walls along contour)	30
Lixisols/Cambisols/Planosols (lowlands)	Ridge-furrow system along the slope	70
Fluvisols/Cambisols (river banks)	Broad bed system	90
Vertisols (lowlands)	Broad bed system	5

Land clearing is done manually, using a machete or an axe depending on the type of vegetation. For rainfed cultivation, land clearing starts in April-May, at the end of the dry season. It starts in September-October for post-rainy season sorghum. After cutting and air drying, burning follows.

The ploughing operations come just after the first rains in May-June. Tillage is done with a hand hoe or an animal-drawn plough, using a pair of oxen or donkeys. Generally, poor farmers use a hand hoe. The ploughing depth varies from 5 to 10 cm with a hand hoe and from 10 to 20 cm with a plough. The ploughing depth varies also with soils and crops. In some cases, the farmers practice minimum or zero tillage operations.

A ridge-furrow system is made after ploughing. Ridges vary from 10 to 30 cm height and from 20 to 50 cm width. The type of equipment and the hardness of the soil surface layers influence the size of the ridges. Bigger ridge-furrow systems are found where ploughing has been performed by animal traction or on less eroded soils where the surface layers are relatively soft. Ploughing with a hand hoe on relatively hard surface layers (more eroded soils) produces small ridge-furrow systems. Ploughing and ridging are done along the slope direction. Most often, the seedbed consists of ploughing only, without any further operation.

The seeds of the cereals are sown along the ridges. Five to six seed kernels are dropped in a small hole 5 to 7 cm deep, made with a hoe, at regularly spaced intervals of about 100 cm. Legumes and other crops are sown in the furrows at variable intervals (10 to 40 cm). Where only ploughing is done, seeds are sown in the rows and the space between the rows is used for legumes and vegetables. Cotton is grown as a single crop. Seeds are sown along the ridges at regularly spaced intervals (25 to 40 cm). The distance between two consecutive ridges is approximately 100 cm.

In the highlands, stone wall terraces have been locally constructed along the contours. Older terraces date more than a century back. The construction of stone wall terraces is a common practice in some tribes of the Gawar area. The terraces are frequently repaired at the end of the dry season. The stone walls vary from 30 to 50 cm wide and from 50 to 75 cm high. The terrace is 0.5 to 2 m large.

Rectangular broad bed systems (diguettes) of varying size are recommended on Vertisols to improve moisture storage during the rainy season. The stored water may be used for post-rainy season cropping. But very few farmers use the practice in the Gawar area.

(2) Biological practices

Biological measures are related to the crop characteristics and the crop management. The objective is to reduce splash erosion by maintaining a good ground cover. The main crop characteristics required are early planting, good stand and optimum plant population, balanced fertilizer applications, adequate weed, insect and disease control, and increased use of farm inputs such as mulch and manure. The rate of adoption of biological measures in the Gawar area is shown in table 6.8.

Table 6.8 Implementation of biological and chemical measures

Biological measures	Farmers' response (%)
High planting density	90
Improved crop varieties	13
Chemical fertilizers	35
Chemicals for weed, insect and disease control	25

(a) High planting density

A high planting density covers the soil surface and protects if from erosion. Plant density varies with crop types. Recommended optimal crop densities (NCRE, 1994) are as follows:

- sorghum: 40,000 to 62,500 plants/ha;
- millet: 25,000 to 30,000 plants/ha;
- maize: 37,500 to 62,500 plants/ha;
- Muskwari sorghum: 20,000 to 30,000 plants/ha;
- cowpea: 25,000 to 100,000 plants/ha;
- groundnut: 70,000 to 100,000 plants/ha;
- cotton: 60,000 to 80,000 plants/ha.

(b) Use of improved crop varieties

The advantage of using improved crop varieties is their fast growing capacity, which establishes a quick ground cover before the rainy season reaches its most erosive period. Many improved varieties have been developed by the Institute for Agronomic Research in Maroua (NCRE, 1994):

- sorghum: S35, CS-54, CS-61, CS-95 and CS-141;
- millet: IKMV and INMV;

- maize: Mexican, SAFITA2, CSM8704, DMR-ESR-Y, CMS8501, CMS8806 and CMS9015;
- cowpea: TVX3236, VYA, BR-1, IT82D-699 and IT8ID-897;
- groundnut: IB-66, JB-77, ICGS-27, M-416 and 55-437; and
- cotton: glandless and gossypol varieties.

Despite the availability of improved crop varieties, many farmers still grow local varieties of rainfed sorghum. Djonnewa (1996) and Ndikawa (1996) reported that there are about 1800 sorghum varieties that differ from one another by colour (red or white), form of the panicle (long or short, open or close), length of the growing cycle (90 to 140 days), resistance to drought and pests, or taste and uses (food, beer brewing or roof construction). The main local varieties of rainfed sorghum are Safrari, Madjeri, Bourgouri, Adjagamari, Soukatari, Mandouweiri and Soulkeiri. Mouskwari sorghum cultivation uses only local varieties.

(3) Chemical practices

Chemical fertilizers are used to speed up the growth of crops, which increases the ground cover and protects the soil surface against erosion. NPK compound fertilizers of variable composition 15-15-15 or 20-20-40 are applied at the rate of 100 kg/ha. They are only used for cotton cultivation, under the supervision of SODECOTON that provides inputs to farmers as loans. Due to high cost, many farmers cannot afford buying chemicals for their food crops.

Chemicals are also used for weed, pest and disease control. Furadan and Marshall are used as insecticides. Thioral is used as fungicide. Chemical weeding may prevent soil from surface disturbances. Hand tool operations loosen the topsoil layers, enhancing erosion.

(4) Erosion control through land husbandry

The objective of erosion control through land husbandry is to offer better land use alternatives, taking into account biophysical factors and the socio-economic environment of the farmers. The land use should at the same time reduce soil erosion and increase production at an acceptable cost. The major farming practices in the Gawar area are mixed cropping, intercropping, relay cropping and shifting cultivation.

About 70% of the crops are produced in a mixed cropping pattern (Djonnewa, 1996). Cereals are mixed with legumes and vegetables. Farmers practice mixed cropping to minimize crop failure, but also to increase the ground cover and protect the soil surface against raindrop impact. In contrast, the monoculture of cotton favors erosion. For instance, the prescriptions by the SODECOTON extension service for cotton cultivation include: (1) complete clearing from plant residues; (2) use of one cotton variety; (3) ploughing and early sowing in rows on ridges; (4) no intercropping or mixed cropping; (5) application of 100 kg/ha of compound fertilizers; (6) four to five applications of chemical biocides; and (7) collective marketing. But many farmers sow over a long period, apply variable amounts of fertilizer, and practice intercropping with cowpea (De Steenhuijsen, 1995), because food crops receive high priority in resource distribution.

Mouskwari sorghum is also produced in a single crop pattern during the dry season when the hazard to rain erosion is negligible.

(5) Importance of the animal husbandry

Animal husbandry is the main activity after agriculture. It is a traditional activity, transferred from father to son. Cattle ownership is largely considered as a store of wealth. Livestock plays the following roles:

- investment and current financial buffer: when the farmers are out of money, they sell for subsistence;
- labor: draft power for ploughing or transportation;
- fertilizer: manure to keep the fertility of the land;
- sociocultural function: prestige and influence;
- provisional function: provision for the future during old age.

The development of agriculture results into the development of animal husbandry, since the expansion of agriculture is associated with the ownership of substantial herds of cattle. Part of the cash income from crops is used to buy cattle. In return, livestock ensures financial income and food security (Teyssier and Ousman, 1996).

6.4.3 Constraints to crop and animal productions

There is a wide range of soil conservation measures and improved crop management to control soil erosion. However, many farmers continue to use crop and land management practices that degrade their farming environment and affect the sustainability of their land. A thorough study on the attitude and perception of the farmers vis-à-vis the soil conservation measures should be undertaken. Hereafter, some of the reasons explaining the low adoption rate of soil conservation measures in the Gawar area are discussed.

(1) Inherent soil characteristics

Many farmers report that the high susceptibility of the soils to erosion is the main constraint to crop production, depleting soil fertility, decreasing the effective rooting depth and reducing soil moisture. Some soil characteristics prevent the farmers from adopting effective soil conservation measures. For instance, the horizon sequence of Lixisols and Planosols consists of a sandy topsoil layer above a very clayey and hard subsoil horizon, which decreases infiltration and promotes runoff. As a consequence, the ridge-furrow system along contours is quickly filled up with sediments. The hardness of the surface layers of eroded soils hampers deep ploughing with the existing farm tools.

(2) Requirements of improved crop varieties

Although improved technologies might reduce erosion, most of them increase labour input and pest problems. The high requirements for chemical inputs, management and labour of the new crop varieties diminish farmers' enthusiasm for the adoption of improved technologies. Generally speaking, the farmers are attached to soil conservation measures, that offer quick and high payoff, reduce the existing risk, and have low input requirement from the farmers. For instance, the improved sorghum S35 variety has a low adoption rate of 13% (NCRE, 1994; Kenga and Abba, 1996), because it is particularly susceptible to bird damage. Moreover, the farmers are attached to crop varieties that provide a wide range of uses. Local sorghum varieties, for example, can be used for multiple purposes: fuelwood, roof construction, fodder, fencing and shade. In contrast, improved sorghum varieties have short stems that are unsuitable for such uses.

Drought resistance also influences the adoption of improved crop varieties. Improved sorghum varieties are less drought-resistant than local varieties. The farmers may start growing without knowing what will be the amount of rainfall. Although chemical fertilizers can be used to overcome drought damage, the efficiency of fertilizers also varies according to rainfall. The effect of fertilizers tends to be negligible in the case of a small rainfall. Excessive vegetation growth due to fertilizers at an earlier growing stage causes soil moisture depletion and affects grain formation at a later growing stage (Arnon, 1987).

(3) Labour availability

Although the demand for labour is seasonal, with peak labour periods at the time of land preparation, sowing, weeding and harvesting, there is still a labour shortage during the cropping seasons. Sowing of sorghum, millet, maize and groundnuts is done first, followed by cotton, cowpea and legumes. Most of the sowing and early weeding occur over six to seven weeks time, which represents about half of the total duration of the rainy season. The family members supply the labor that is not always enough. Additional labor cannot be hired, partly because there is no one to hire since everybody is busy with his own farm activities, and partly because there is no money to pay for it. The post-rainy season Mouskwari sorghum is established when rainfed crops need to be harvested, to avoid damage from pests and diseases, which enhances labour shortage.

(4) Equipment suitability

Most of the farm activities are done with a hand hoe. There are no appropriate small farm tools to overcome critical periods of land preparation, planting and weeding, so that farmers can cope with the shortness of the rainy season.

(5) Weeds, pests and diseases

Reduced sorghum and millet productions due to weeds (*Striga hermonthica*) are common. Eroded soils are susceptible to weed growth. Pests such as army worms (*Spodoptera spp*), head bugs and fungal diseases decrease the yields. Storage pests and diseases reduce the food stocks.

(6) Land ownership

The perception of the land by the farmers has changed. According to traditional belief, the farmer belongs to the land, meaning that any harm to the land makes it "angry". In the past, land-related cultures aimed at conserving the land. For instance, a farmer was not allowed to crop or cut a tree on his own decision. Many forested areas, mainly located in the mountains, were managed for traditional ceremonies. Nowadays, the land may belong to a person who can hire it to farmers. This implies reduced care since the land user is not the owner. Many farmers think that the land belongs to the government or related persons, because they can be easily moved away from their farms.

In fact, for agricultural purposes, land use rights are obtained by clearing a field, after consulting the chief of the village, called "Lawan" in the local dialect. The final owner of the land at regional level is the "Lamido", who occupies the highest position in the hierarchy of the traditional community. The "Lamido" works closely with the government. However, this procedure of getting a piece of land does not apply to cattle owners, who are allowed to graze their animals on natural pastures, fallow areas or cultivated areas after harvesting. Under these circumstances, many farmers feel their land unprotected since it can easily be withdrawn. This hampers the adoption of soil conservation measures.

(7) Farming vocation

Farming activities are being undertaken by younger generations that often lack practical experience. Young farmers mainly consist of former students, who did not find office jobs and came back to farming for survival reasons, with the expectation to return to cities. This behaviour may inhibit the capability and vocation of farming.

(8) Costs of soil conservation

Lack of farm tools such as ox-plough and tractor, scarcity of inputs, high costs of available inputs and insufficient farm cash income are referred to as constraints to agriculture development in the Gawar area. In fact, the farmers are reluctant to conservation measures that do not provide short-term income or reduce their income, since they have to rely on their individual resources. Economic incentives to the farmers are necessary for the adoption of soil conservation measures.

(9) Fodder availability

The main constraint to livestock development is the lack of fodder, associated with the scarcity of land and the drying of water ponds. According to Klein and Rippstein (1991), the carrying capacity under the existing conditions should be 1 Tropical Livestock Unit (TLU)/2.5 ha. But the effective value is 1 TLU/ha, which causes fodder shortage. The high evapotranspiration of the area causes the water ponds to dry up, resulting in substantial losses of animals due to dehydration. Acute fodder and water shortage results into a change in the livestock composition. The large ruminants (cattle) are replaced by small ones (goats and sheep).

6.5 REHABILITATING SEVERELY ERODED VERTISOLS

Chemical fertilizer application to replace the nutrients lost in eroded soils failed to ensure crop production in the Gawar study area. Aina (1979) and Meyer et al. (1985) reported that physically degraded soils do not always respond to chemical fertilizer inputs. Eroded Vertisols have good chemical properties, but poor physical and morphological properties that substantially limit crop production. In an experiment on severely eroded Vertisols, simple surface practices, including ridge-furrow system, tied ridging, microcatchment and control plot, were undertaken to examine their effect on the growth of rainfed sorghum (Sorghum S35). The design aimed at controlling runoff, conserving water by storage and improving infiltration. No chemicals were applied so that crop development and behaviour expressed only the effect of the soil-moisture relationships.

6.5.1 Variations in the sorghum response

The rainfall in the crop growing season was quite favorable, at about 900 mm. Sorghum behaviour and production vary considerably according to agricultural practices (table 6.9).

Table 6.9 Sorghum behaviour under different agricultural practices

Agricultural practices	Plant stand at day 45 (%)	Plant stand at day 90 (%)	Root length at day 90 (cm)	Plant height at day 90 (cm)	Dry weight (t/ha)	Grain yield (t/ha)
Control plot	73	65	17	80	0.23	0.03
Tied ridging	89	85	40	183	2.07	0.70
Ridge-furrow system	100	100	41	190	2.11	0.84
Microcatchment	100	100	52	210	3.51	1.30

Sorghum grew much better on microcatchment than on ridge-furrow system, tied ridging and control plot. On control plot and tied ridging, the plant stand decreased with time, whereas the full stand remained constant on ridge-furrow system and microcatchment. The values of the plant stand are 73 and 89% at day 45 after sowing, 65 and 85% at day 90 after sowing, on control plot and tied ridging, respectively. On ridge-furrow system and microcatchment, the value of the plant stand is 100%, at both, day 45 and day 90, after sowing.

The height of the plants at harvesting (day 90 after sowing) is on the average 210 cm on microcatchment and 80 cm on control plot. The tied ridging and ridge-furrow system exhibit intermediate values of plant height at day 90 after sowing. The root length at day 90 after sowing shows similar behaviour. On average, the values of the root length are 52, 41, 40 and 17 cm on microcatchment, ridge-furrow systems, tied ridging and control plot, respectively.

The dry weight of the above-ground biomass, measured at day 90 (harvesting), is high on microcatchment (3.51 t/ha) and low on control plot (0.23 t/ha). On the ridge-furrow system and tied ridging, the dry weight is 2.11 and 2.07 t/ha, respectively.

The grain yield shows a similar trend. Grain production is high on microcatchment (1.3 t/ha), whereas it is low on control plot (0.03 t/ha). The grain yield is moderate on ridge-furrow system and tied ridging (0.84 and 0.70t/ha, respectively). In the semiarid area of Cameroon, sorghum grain yield varies between 1.5 and 2.2 t/ha on slightly eroded soils, under optimal conditions of soil management and chemical applications (Jerry and Fobasso, 1987).

6.5.2 Effect of the agricultural practices

An increase of yield in the absence of chemical fertilizers suggests that the deterioration of the soil-water supply, as a consequence of erosion, might be the most limiting factor on severely eroded Vertisols. The variations in grain yield and other crop performance parameters can be attributed to the differences in the capability of the agricultural practices to collect, retain and store rain water for crop development. The advantage of microcatchment is that the separate semi-circular bunds reduce the risk of damage from surface runoff by spreading excess runoff laterally. In addition, the microcatchment structure provides better conditions to collect and conserve rain water; this enhances soil moisture content and increases sorghum yields. However, a high exposure of microcatchment to raindrop impacts increases erosion, requiring continuous maintenance throughout the duration of the rainy season.

A fast disposal of the rain water on the ridge-furrow system decreases water retention and causes soil moisture shortage during dry spells, reducing the grain yields. Tied ridging presents a high risk of overtopping of the ridges, when surface storage is exceeded during heavy storms. In fact, the sorghum plants were moderately chlorotic during growth on tied ridging, indicating that the plants may have been affected by temporary waterlogging. The control plot offers a small capacity of water collection and storage, causing low yields.

Considering the yields normally achieved by farmers on severely eroded soils without soil surface management, comparable to the yield of the control (less than 0.05 t/ha), the sorghum grain yields of 0.7 to 1.3 t/ha obtained on severely eroded soils with simple surface practices are quite high. Compared to the control plot, the yields are 43 times higher on microcatchment, 28 times higher on ridge furrow system, and 23 times higher on tied ridging. Thus yields can be substantially improved when applying appropriate soil-water storage and management practices. Yield improvement could help decrease the pressure on extending the cropping area, which causes competition and land use conflicts among different land users.

Although similar experiments should be conducted at least three to five years on major soil types before fully documenting the effect of the practices on crop production, it seems however possible that simple surface practices, as described in this section, can increase grain sorghum yield. This could ensure self-sufficient food production for human and animal populations in the Gawar area.

6.6 CONCLUSION

Farming systems at each of the three spatial scales considered, including regional scale, local scale and farm scale, vary according to the diverse soil and climatic conditions. Despite a relatively high diversity in farming systems, the farmers still produce at subsistence level. Sustainable agricultural development at acceptable yields must be based on the interactions between production-oriented farming systems and environmental conservation measures. The results of the sorghum experiments on severely eroded Vertisols reveal that agricultural practices, that are at the same time appropriate to the environment and economically profitable to the small farmers, can be achieved in the Gawar area.

CHAPTER 7

SURFACE RUNOFF HYDROGRAPHS

Artificial rainfall was produced on twenty five sites, representing the regional soil types with different erosion classes. Three erosion classes were identified for each soil type, including (1) slightly eroded, (2) moderately eroded, and (3) severely eroded. Three rain showers were simulated at different intensities and durations. Plots were bare and ploughed with a hand hoe. A first shower or pre-wetting rain (rain 1) was applied to the bare soil surface. The surface runoff hydrograph of each of the two consecutive simulated rains (rain 2 and rain 3) on each of the selected soils were established and the unit hydrograph parameters defined.

7.1 VARIATIONS IN SURFACE RUNOFF HYDROGRAPH PROFILES

7.1.1 Variations within rainfall events

All the surface runoff hydrographs evidence a sequence of four phases during a rain shower. As illustrated by figures 7.1 and 7.2, the first phase is composed of successive short stages of increasing runoff rate. During the second phase, relatively longer periods of steady-state runoff rates take place. The third phase corresponds to the peak runoff. During the last phase, runoff rate decreases to the level of baseflow recession.

(a) (b)

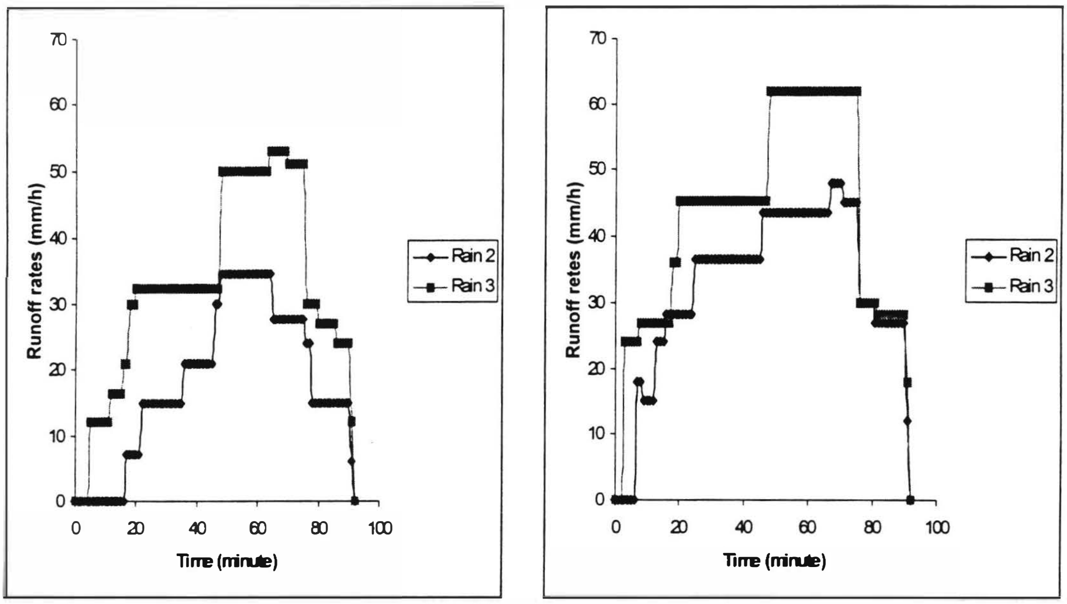


Figure 7.1 Surface runoff hydrograph profiles showing variations of runoff rate (a) on slightly eroded Lixisols, and (b) on moderately eroded Lixisols.

(a) (b)

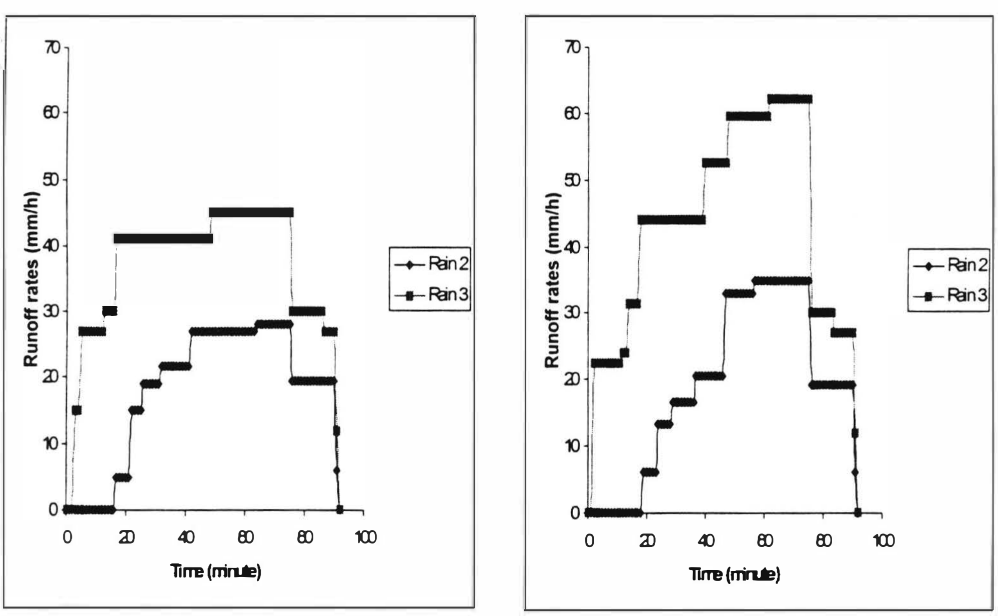


Figure 7.2 Surface runoff hydrograph profiles showing variations of runoff rate (a) on slightly eroded Planosols, and (b) on moderately eroded Planosols.

(1) Phase of successive short periods of increasing runoff

After the infiltration is satisfied, rainfall water begins to fill the interconnected small depressions on the soil surface. As rainfall intensity and duration increase, larger depressions are filled. Surface overland flow begins. This causes the destruction of the micro-depressions and generates substantial runoff. Successive filling and destruction of depressions of different sizes are translated into small periods of increasing runoff rates. The segment of the surface runoff hydrograph, from the start to peak of the runoff, is called rising limb of the hydrograph. Some surface runoff hydrographs (figure 7.3) show a short period of decreasing runoff during the rising limb of the surface runoff hydrograph or during the steady-state runoff. This is probably due to sudden collapse of the soil surface during the experiments, which creates macro-depressions or macropores that retain part of the overland flow and decrease runoff rates.

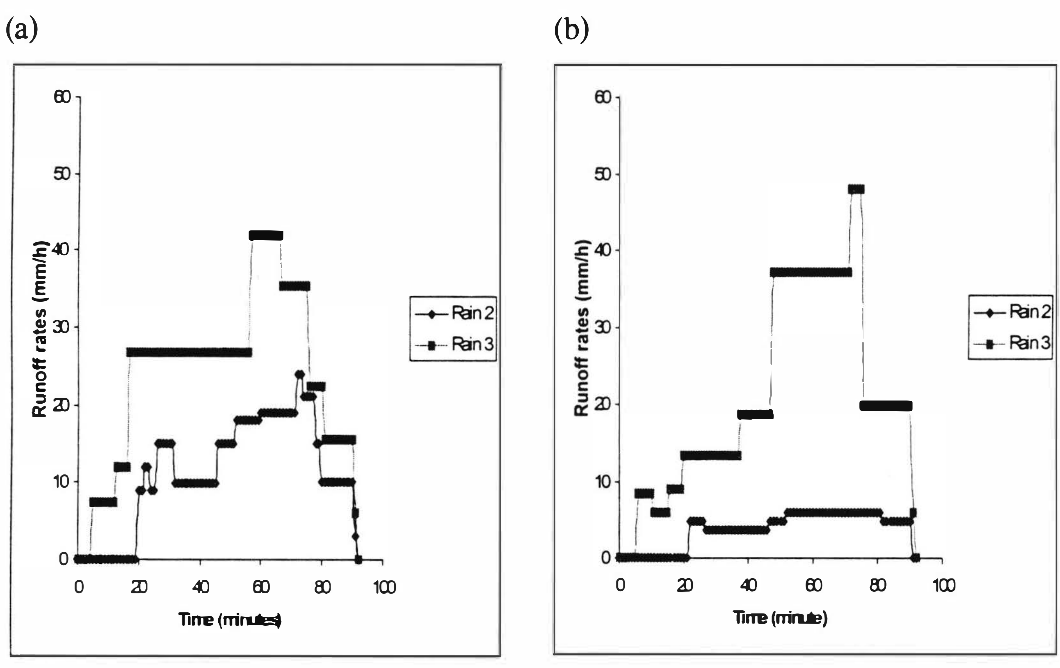


Figure 7.3 Surface runoff hydrograph profiles showing sudden runoff decreasing during the rising limb phase (a) on moderately eroded Lixisols, and (b) on severely eroded Lixisols.

(2) Phase of steady-state of runoff

As the rain proceeds, the topsoil layer becomes saturated and most of the micro-depressions are destroyed. The soil surface opposes only small resistance to the advance of the overland flow. So most of the additional rain simply runs off and causes a constant runoff rate, controlled by interactions between rain characteristics and soil properties that regulate percolation.

(3) Phase of peak runoff

After topsoil saturation, the highest runoff rate is reached with the highest rainfall intensity, and it lasts approximately as long as the duration of this rainfall.

(4) Phase of decreasing runoff

As rainfall intensity decreases during the post-peak runoff period, runoff rate decreases and reaches the value zero just after the cessation of the rain. The line connecting the peak runoff and the point where runoff rate equals zero is called the falling limb of the surface runoff hydrograph.

7.1.2 Variations between rains

The surface runoff hydrograph profiles derived from two consecutive simulated rains on experimental plots change in the duration of the different phases. For instance, the duration of the first phase decreases (figure 7.4). The duration of the second and fourth phases increases, whereas that of the third one remains almost constant, with increasing rainfall characteristics in terms of rainfall intensity, duration and number of events. This behaviour can be explained partly by the changes in the soil surface microtopography, with decreasing soil surface roughness and increasing crust formation, and partly by topsoil saturation which promotes earlier and higher runoff with increasing rainfall characteristics.

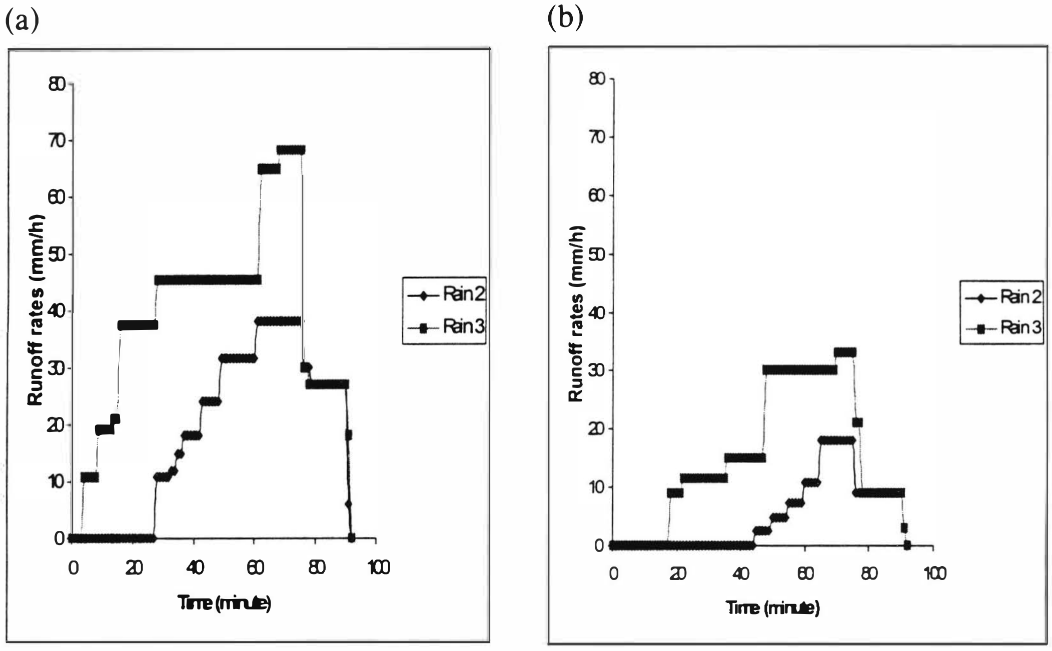


Figure 7.4 Surface runoff hydrograph profiles showing variations in the duration of the different phases between rains (a) on moderately eroded Vertisols, and (b) on slightly eroded Fluvisols.

7.1.3 Variations between soils

The surface runoff hydrograph profiles also change according to soil types. Two situations can be distinguished. In the first one, the surface runoff hydrograph consists of a short phase of increasing runoff rates, followed by a long phase of steady-state runoff (figure 7.5). This pattern may indicate soils with a high susceptibility to crust formation (figure 7.5a) or to quick topsoil saturation (figure 7.5b). In fact, during the post-crust-formation or post-topsoil-saturation periods, runoff hydrographs mainly express the rainfall characteristics. The soils showing this pattern of the surface runoff hydrograph are slightly and moderately eroded Lixisols and slightly and moderately eroded Planosols.

In the second situation, the surface runoff hydrographs exhibit a relatively long phase of increasing runoff rates followed by a short phase of steady-state runoff (figure 7.6). Moderately eroded Cambisols and severely eroded Vertisols exhibit this pattern of the surface runoff hydrograph. A longer phase of increasing runoff may reflect a relatively continuous formation of microtopographic depressions due to selective erosion.

(a) (b)

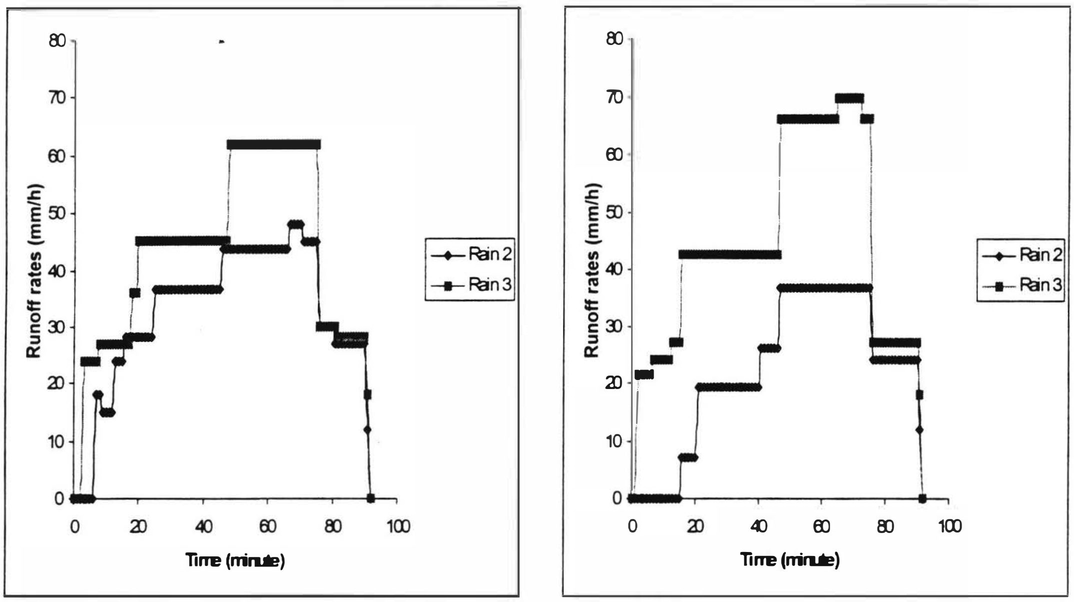


Figure 7.5 Surface runoff hydrograph profiles showing the effect (a) of crusting soil surface on moderately eroded Lixisols, and (b) of topsoil saturation overland flow on severely eroded Planosols.

(a) (b)

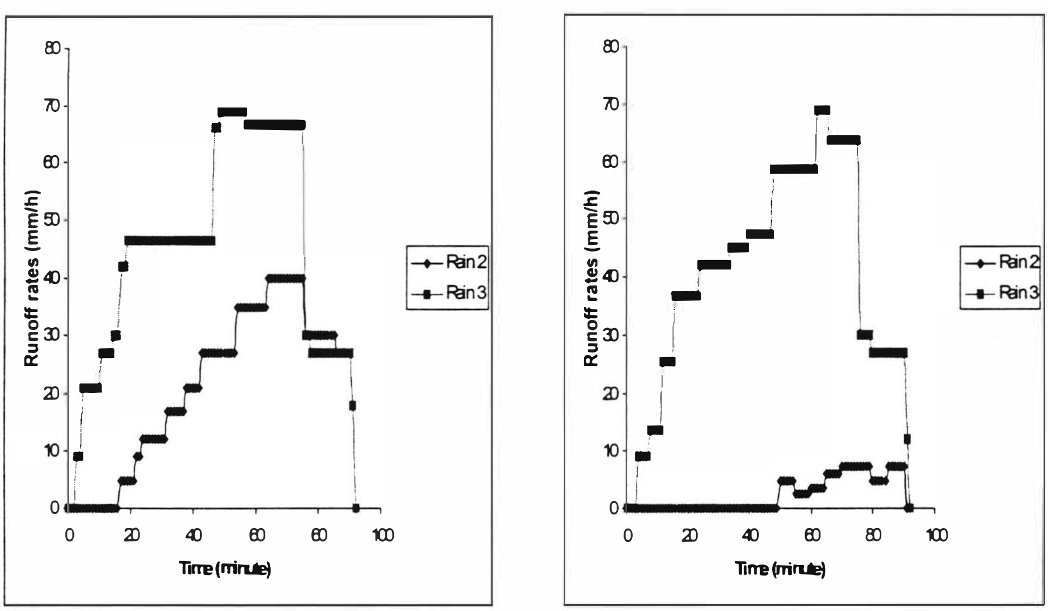


Figure 7.6 Surface runoff hydrograph profiles for selective erosion of the soil surfaces (a) on moderately eroded Cambisols, and (b) on severely eroded Vertisols.

7.2 CHANGES IN RUNOFF HYDROGRAPH PARAMETER VALUES

7.2.1 Variations between rains

Surface runoff hydrograph parameter values derived from rain 2 and rain 3 are presented in table 7.1 and table 7.2, respectively, showing variations of the depression storage and runoff between rains.

(1) Depression storage

In the second rain, 76% of the experimental plots show values of depression storage that vary between 1 and 2 mm. Only 16% of the plots have depression storage values lower than 1 mm. Plots on slightly eroded Cambisols and slightly eroded Vertisols (plot 23 and plot 6 in table 7.1, respectively) did not produce runoff and were therefore allocated an arbitrary depression storage value of 150 mm.

In the third rain, the depression storage drops to values varying between 0.2 and 0.5 mm for 23 plots, representing 92% of all experimental plots. Only one plot, on slightly eroded Cambisols (plot 23 in table 7.2), displayed a value of 2 mm. The plot on slightly eroded Vertisols did not produce runoff and was therefore allocated an arbitrary depression storage value of 150 mm.

The substantial decrease and uniformization of the depression storage values observed in the third rain suggest that soil surface conditions, originally significantly variable between soils because of surface roughness differences, became more homogeneous with rainfall duration because of flattening and crusting of the soil surface.

Table 7.1 Surface runoff hydrograph parameter values derived from the rain 2

Soil characteristics			Surface runoff hydrograph parameters								
Soil types	**Erosion classes**	**Plot**	**Time to ponding (minute)**	**Time to runoff (minute)**	**Time to peak runoff (minute)**	**Hydrograph duration (minute)**	**Depression storage (mm)**	**Peak runoff rate (mm.h^{-1})**	**Rising limb slope (mm h^{-1} min^{-1})**	**Runoff (mm)**	**Runoff coefficient (%)**
Lixisols	Slightly eroded	7	14	16	47	75	1.1	35	1.1	27	41.7
	Moderately eroded	3	22	24	67	67	1.3	51	1.2	29	43.8
		4	17	19	71	72	1.3	24	0.5	17	26.2
		14	15	17	66	74	1.3	18	0.4	15	23.1
		18	5	6	66	85	0.5	48	0.8	49	75.5
		24	15	17	66	74	1.3	42	0.8	32	49.8
	Severely eroded	16	19	21	51	70	1.3	6	0.2	6	8.8
		19	27	29	68	62	1.3	30	0.8	22	33.5
Vertisols	Slightly eroded	6	150*	150*	150*	0	150	0	0	0	0
	Moderately eroded	11	18	20	68	71	1.3	30	0.6	27	41.1
		17	25	27	60	64	1.3	38	1.1	28	42.3
	Severely eroded	21	47	49	69	42	2	7	0.3	4	5.7
Cambisols	Slightly eroded	2	48	49	65	42	1	6	0.4	2	3.7
		23	150*	150*	150*	0	150*	0	0	0	0
	Soderately eroded	10	12	14	65	77	1	27	0.5	25	38.9
		20	14	16	63	75	1.1	40	0.8	32	49.1
	Severely eroded	1	19	21	73	70	1.3	36	0.7	26	40.6
		5	22	24	60	67	1.3	36	1	20	31.4
Fluvisols	Slightly eroded	9	43	44	64	47	0.6	18	0.9	8	11.7
	Moderately eroded	22	31	32	70	59	1	30	0.8	20	31.2
Leptosols	Severely eroded	12	14	15	48	76	0.5	27	0.8	27	41.2
Planosols	Slightly eroded	15	14	16	63	75	1.3	28	0.6	27	42.0
	Moderately eroded	13	16	18	56	73	1.3	35	0.9	29	43.8
	Severely eroded	8	12	14	55	77	1	30	0.7	23	36.0
		25	13	15	46	76	1	37	1.2	34	51.5

Remark: (*) indicates that runoff did not occur

Table 7.2 Surface runoff hydrograph parameter values derived from the rain 3

Soil characteristics			Surface runoff hydrograph parameters								
Soil types	**Erosion classes**	**Plot**	**Time to ponding (minute)**	**Time to runoff (minute)**	**Time to peak runoff (minute)**	**Hydrograph duration (minute)**	**Depression storage (mm)**	**Peak runoff rate ($mm.h^{-1}$)**	**Rising limb slope ($mm\ h^{-1}\ min^{-1}$)**	**Runoff (mm)**	**Runoff coefficient (%)**
Lixisols	Slightly eroded	7	3	4	63	87	0.5	53	0.9	50	58.6
	Moderately eroded	3	6	7	55	84	0.5	40	0.8	40	47.0
		4	3	4	56	87	0.5	42	0.8	36	42.8
		14	0.5	1	51	90	0.2	54	1.1	59	69.3
		18	1.5	2	47	89	0.2	62	1.4	65	76.7
		24	1	2	66	89	0.5	71	1.1	69	81.6
	Severely eroded	16	4	5	71	86	0.5	48	0.7	32	37.6
		19	4	5	47	86	0.5	56	1.3	56	66.4
Vertisols	Slightly eroded	6	150*	150*	150*	150*	150*	0	0	0	0
	Moderately eroded	11	4	5	47	86	0.5	47	1.1	50	59.4
		17	2	3	67	88	0.5	68	1.1	59	69.3
	Severely eroded	21	2	3	61	88	0.5	69	1.2	62	72.8
Cambisols	Slightly eroded	2	11	12	63	79	0.5	36	0.7	23	27.5
		23	43	45	64	46	2	19	1	7	8.5
	Moderately eroded	10	0.5	1	57	90	0.2	50	0.9	49	58.1
		20	1	2	48	89	0.5	69	1.5	68	79.9
	Severely eroded	1	2	3	59	88	0.5	54	1	44	52.2
		5	4	5	71	86	0.5	51	0.8	43	51.1
Fluvisols	Slightly eroded	9	16.5	17	69	74	0.5	33	0.6	23	27.3
	Moderately eroded	22	2.5	3	69	88	0.2	60	0.9	58	68.4
Leptosols	Severely eroded	12	4.5	5	53	86	0.2	42	0.9	46	53.8
Planosols	Slightly eroded	15	1	2	48	89	0.5	45	1	56	65.4
	Moderately eroded	13	0.5	1	61	90	0.2	62	1	65	76.9
	Severely eroded	8	6	7	53	84	0.5	45	1	42	49.2
		25	0.5	1	64	90	0.2	70	1.1	67	78.6

Remark: (*) indicates that runoff did not occur

(2) Runoff

Runoff characteristics vary considerably with time. Runoff starts earlier and is more abundant during the third rain than during the second rain. For instance, on slightly eroded Lixisols (plot 7 in tables 7.1 and 7.2), the time to runoff is sixteen minutes in the second rain, but only four minutes in the third one. The peak runoff rates are 35 and 53 mm/hr and the runoff amounts are 27.1 and 49.8 mm in the second and the third rain, respectively. The runoff coefficient increases by various orders of magnitude between the second and the third rain, with values changing either strongly or moderately, or remaining constant.

(a) Strong variations

Strong variations are found on severely eroded Vertisols. Peak runoff and runoff coefficient values are 7 mm/h and 5.7% after the second rain, but increase to 69 mm/h and 72.8% during the third rain. A similar behavior is observed on moderately eroded Planosols, moderately eroded Lixisols that have high concentration of coarse fragments in the profile, moderately eroded Cambisols and moderately eroded Entisols.

(b) Moderate variations

Variations in runoff characteristics are moderate on slightly and moderately eroded Fluvisols, and on severely eroded Leptosols. The runoff coefficient varies between 23 and 50% in the second rain, and between 27 and 80% in the third rain.

(c) No variations

Despite substantial increase in rainfall intensities and durations during the third rain, no variations with time were observed on slightly eroded Vertisols and some moderately eroded Lixisols (tables 7.1 and 7.2). While there is no runoff on the former, the later have a relatively constant runoff coefficient between the second (75.5%) and the third rain (76.7%).

The differences in runoff response suggest that two processes blocking infiltration have taken place simultaneously at the soil surface during the simulated rains. Firstly, an increase of soil moisture in the topsoil layer and the filling of the microtopographic depressions at the soil surface accelerate the circulation of the overland flow. Secondly, surface sealing restricts infiltration and enhances runoff. The consequence of this is that the late runoff mainly expresses rainfall characteristics. Levy et al. (1994) report similar results.

7.2.2 Variations between soil types

The total runoff amounts produced on the different soil classes were compared. The relative susceptibility to runoff production of the soil classes changes according to erosion classes. For instance, on slightly and severely eroded soils, the order is: Vertisols < Cambisols < Fluvisols < Lixisols < Planosols. But on moderately eroded soils, the order is: Fluvisols < Vertisols < Planosols < Cambisols < Lixisols (figure 7.7).

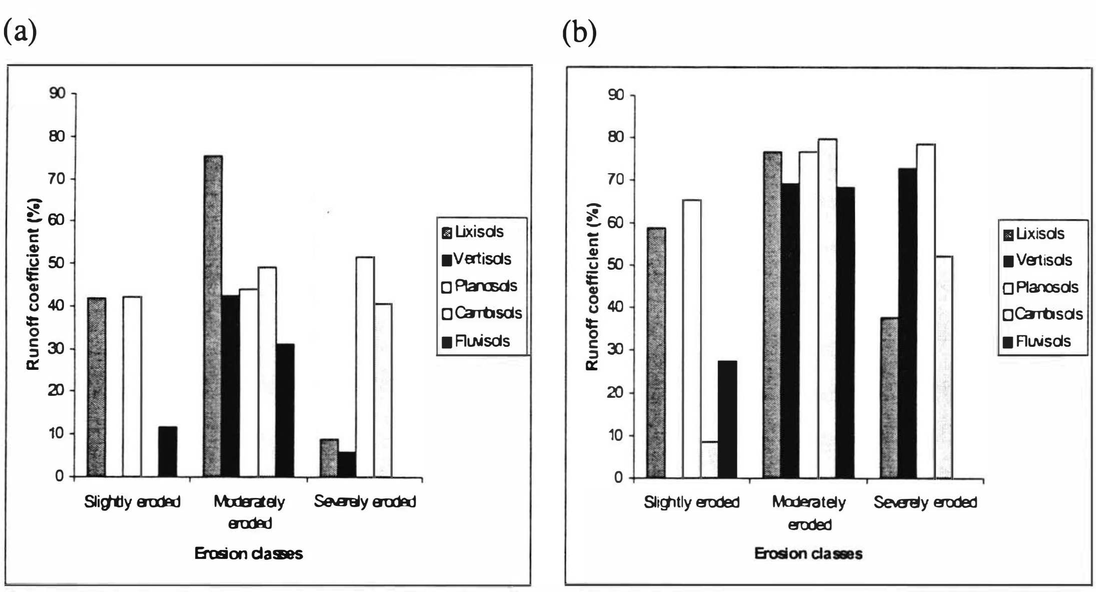


Figure 7.7 Runoff coefficient on different erosion classes of the selected soil types in the second rain (a) and the third rain (b).

On Vertisols, cracks absorb the rainfall water, and it is only after closing of the cracks that runoff starts. This requires a great amount of rain and, under natural conditions, cracks close only during the second half of the rainy season. Vertic Cambisols behave like Vertisols, while Cambisols and Fluvisols with sandy layers favor infiltration and retard runoff.

Considerable seepage flow from the infiltrated water was observed during simulated rainfall experiments on Leptosols on steep slopes, indicating that part of the water which penetrates the topsoil layer is blocked by the bedrock and runs over it as base flow before rising out downslope.

The horizon sequence in Lixisols and Planosols includes coarse-textured topsoil layers (Ap and A2) above heavy, hard and structureless subsoil layers (Btd and Bt). As permeability and runoff depend on the least permeable horizon in the layer sequence, Bt horizons promote saturation overland flow (De Ploey, 1986; Kuipers, 1986). Contrasting layers result in high runoff production, which contributes to the deterioration of the surface structure and the structural stability.

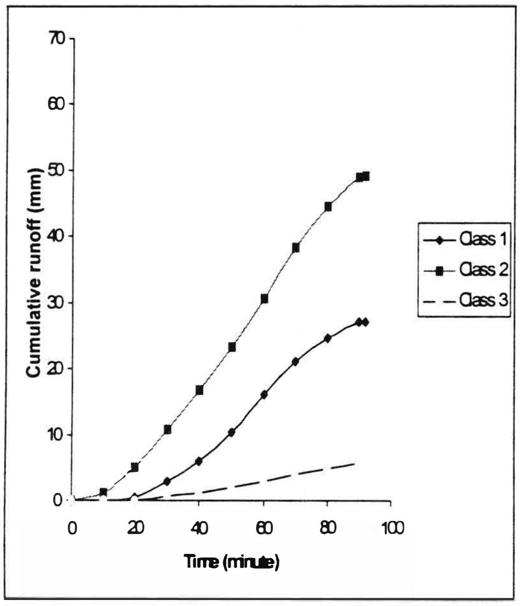
Rock fragments have an ambivalent effect on runoff generation. A high concentration of rock fragments at the soil surface favors infiltration and increases the area of the topsoil being protected against raindrop impacts. But the same factor, especially in presence of flat rock fragments, may also contribute to rapid runoff generation. Fletcher and Bentner (1941), Poesen et al. (1990) and Poesen and Ingelmo-Sanchez (1992) report similar behavior.

7.2.3 Variations between erosion classes

As expected, erosion classes show differences in runoff. On Lixisols (figure 7.8), the order of increasing susceptibility to runoff production is: severely eroded < slightly eroded < moderately eroded. On Vertisols (figure 7.9) and Planosols (figure 7.10), the order of increasing susceptibility to runoff production in the last rain is indicated by:

slightly eroded < moderately eroded < severely eroded. Whereas on Cambisols (figure 7.11) and Fluvisols (figure 7.12), the order of increasing susceptibility to runoff generation is: slightly eroded < severely eroded < moderately eroded. The general tendency is that more eroded soils produce more runoff. This may vary over a considerable range, such as on Vertisols with no runoff on slightly eroded soils but a coefficient of runoff of 69.3% on severely eroded soils during the last rain. Thebe (1987), Seiny (1990) and Mahop et al. (1995) report similar orders of magnitude.

(a) (b)



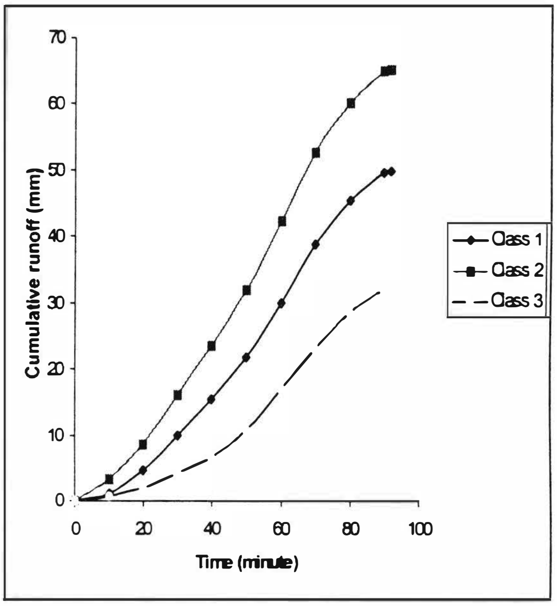


Figure 7.8 Cumulative runoff on slightly eroded Lixisols (class 1), moderately eroded Lixisols (class 2) and severely eroded Lixisols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

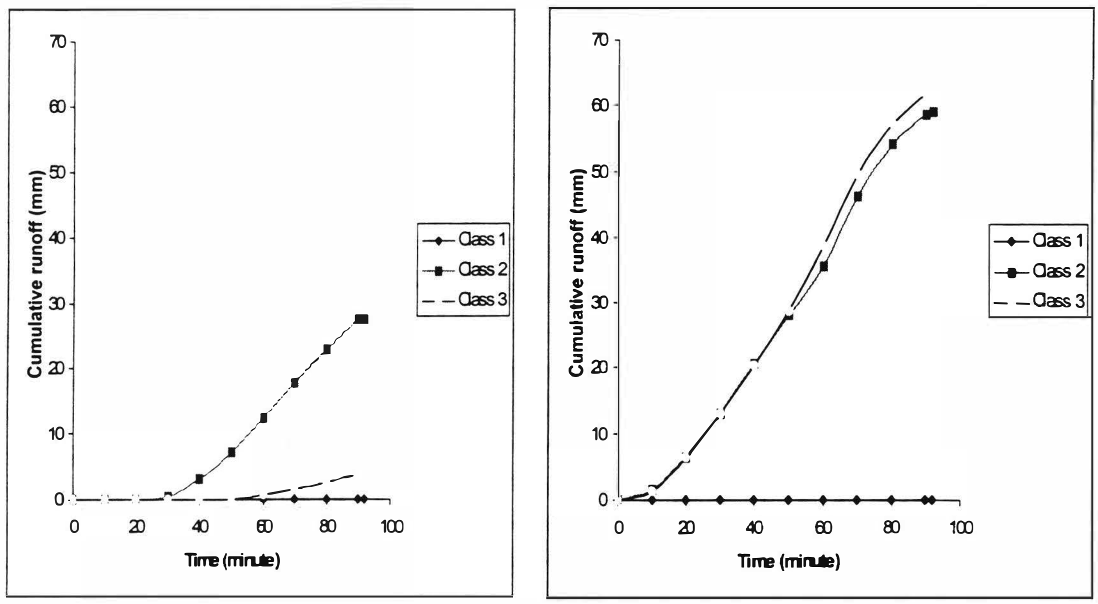


Figure 7.9 Cumulative runoff on slightly eroded Vertisols (class 1), moderately eroded Vertisols (class 2) and severely eroded Vertisols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

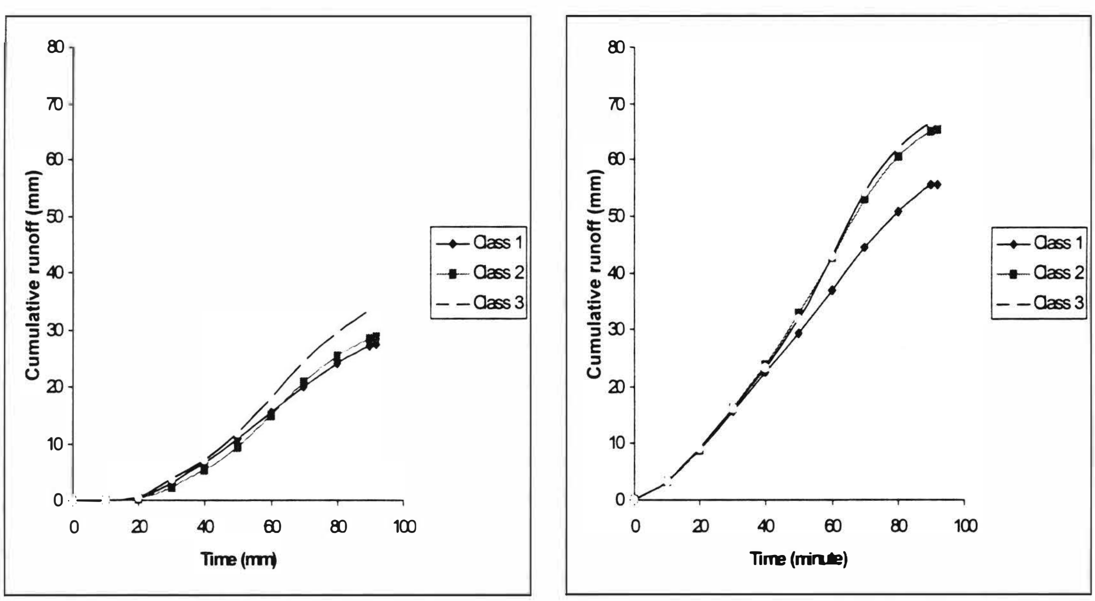


Figure 7.10 Cumulative runoff on slightly eroded Planosols (class 1), moderately eroded Planosols (class 2) and severely eroded Planosols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

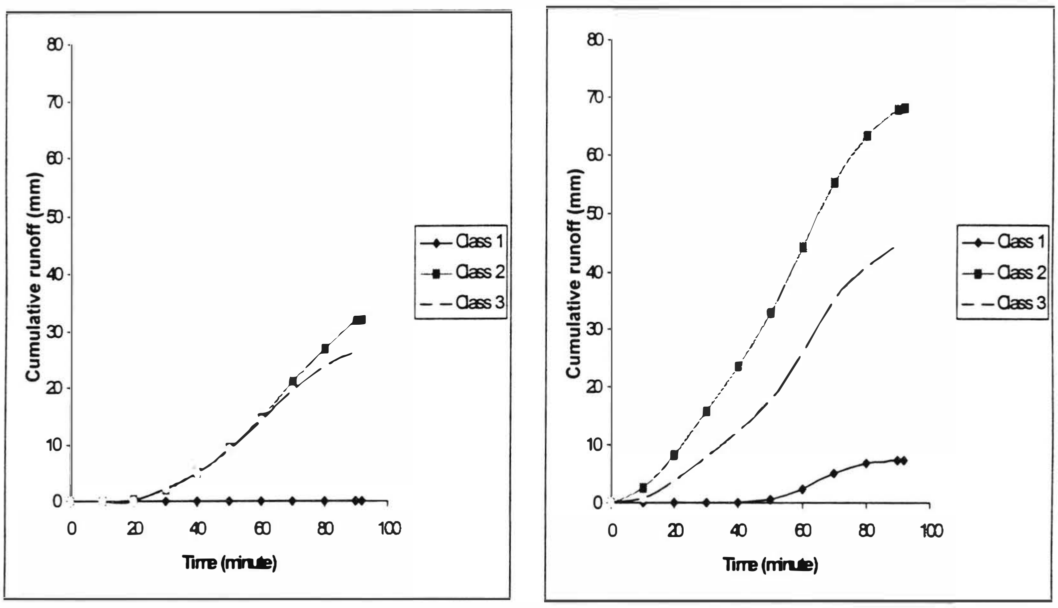


Figure 7.11 Cumulative runoff on slightly eroded Cambisols (class 1), moderately eroded Cambisols (class 2) and severely eroded Cambisols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

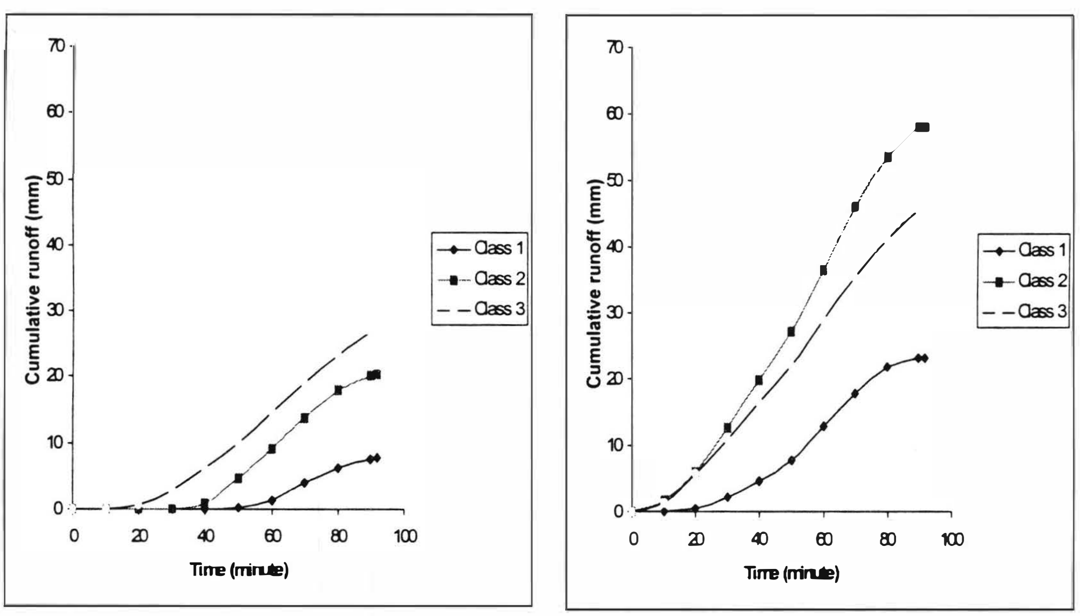


Figure 7.12 Cumulative runoff on slightly eroded Fluvisols (class 1), moderately eroded Fluvisols (class 2) and severely eroded Leptosols (class 3) in the second rain (a) and the third rain (b).

The differential behavior of the erosion classes can be attributed to the modifications that affect the topsoil characteristics, such as clay and organic matter contents, and the thickness of the topsoil layers according to erosion degrees (Lal, 1988). More eroded soils (Lixisols and Planosols) have a higher clay content (>20 %) in the surface horizons than less eroded ones. A higher clay content promotes a stronger cohesion of the soil surface aggregates, which resist slaking. Resistant clods maintain the depression storage, enhance infiltration and retard runoff. In contrast, less eroded soils present thicker topsoil layers (>15 cm) and higher organic matter content (0.5-1%) than more eroded ones, providing larger water storage capacity. But as rainfall proceeds, saturation overland flow occurs and the apparent resistance of eroded soils to runoff consistently decreases. On moderately and severely eroded Vertisols, cracks are less efficient in absorbing water.

7.3 CONCLUSION

The erosion classes of the major soil types in the semiarid area of north Cameroon show different degrees of susceptibility to runoff generation. Eroded soils are more susceptible than less eroded ones. The difference in runoff response can be attributed to the modifications that affect the characteristics of the topsoil layers due to previous erosion. For instance, organic matter contents and thickness of the topsoil layers negatively correlate with erosion severity and with runoff. The variations of runoff according to soil classes, the differences that occurred between soil classes are related to differences in soil properties that control permeability and regulate infiltration and percolation, such as structure, texture and horizon sequence. These results agree with those obtained by Pontanier et al. (1984), Thebe (1987), Seiny (1990) and Mahop et al. (1995). But the present investigation goes further and highlight the surface runoff hydrographs which reflect the processes occurring within a rainfall event, between rains and between soils.

CHAPTER 8

SPLASH AND INTERRILL EROSION

Twenty five sites, representing the regional soil types with different erosion classes, were subjected to artificial rainfall. Three erosion classes were identified for each soil type, namely slightly eroded, moderately eroded and severely eroded. A field rainfall simulator was used for studying erosion at one-square-meter plots. Three rain showers were simulated at different intensities and durations. Plots were bare and ploughed with a hand hoe. The method allowed explicit consideration of the factors determining both runoff and sediment concentration in detail. Samples of splashed-off and runoff material were taken every ten minutes throughout each simulated rain. A first shower or pre-wetting rain (rain 1) was applied to the bare soil surface. Data of erosion parameters obtained during rain 2 and rain 3 were compared to describe and evaluate spatial and temporal changes in splash erosion and interrill soil loss.

8.1 SPLASH EROSION

8.1.1 Changes over time

(1) Variations within rainfall events

Rates of soil detachment by raindrop impacts vary considerably within each simulated rainfall event. Three distinct phases occur regarding temporal variations of splash detachment rates. During the first phase, rates of splash sediment increase. During the second one, splashed soil particle rates tend to decrease. The last phase exhibits a constant rate of splashed sediment.

(a) Phase of increasing splash rates

Splash detachment rates increase with time on severely eroded Vertisols and severely eroded Cambisols (figure 8.1). This is probably due to cohesion loss of the aggregates in the topsoil layer, which enhances detachability of soil particles. Continuous moistening reduces the cohesion of the soil aggregates through slaking, which enhances splash detachment. Coutts et al. (1968), Cruse and Larson (1977), Bradford et al. (1987) and Parson (1994) report similar results. They attribute the increasing splash rate, prior to ponding, to decreasing shear strength and aggregate stability with increasing soil moisture content. Exposure of the soil surface aggregates to raindrop impact can also explain the increase of splash rates with time. For instance, the high infiltration on slightly eroded Vertisols does not allow the formation of only water film on the soil surface, which exposes soil surface aggregates and enhances splash detachment. The formation of a water film at the soil surface reduces the raindrop energy and decreases splash detachment.

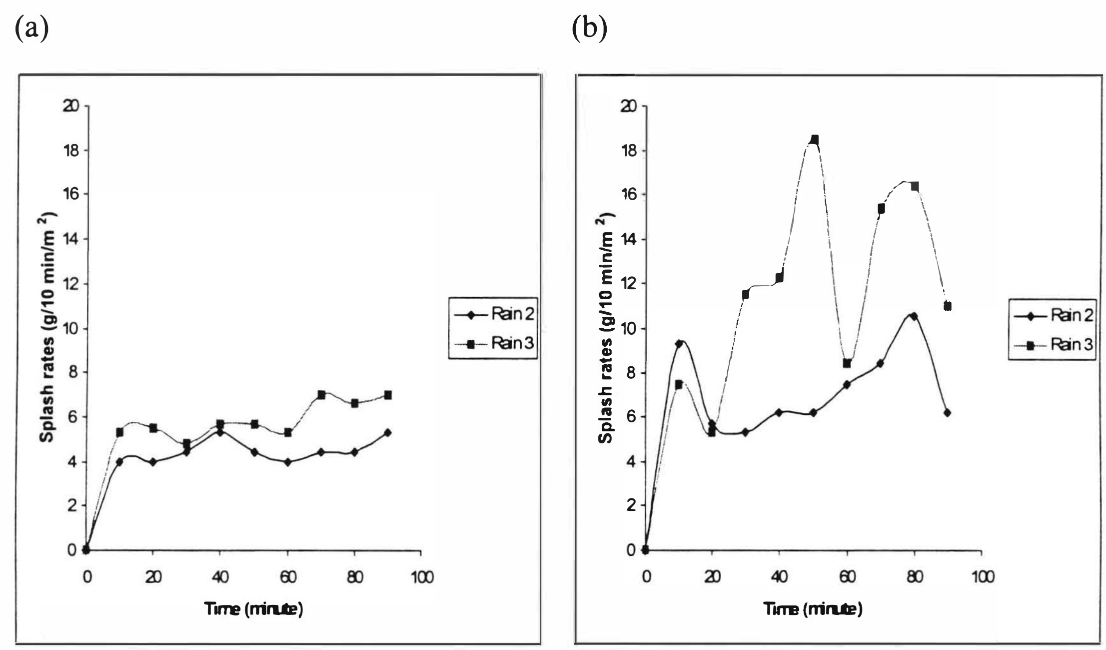


Figure 8.1 Temporal variations of splash erosion with increasing splash detachment rates (a) on severely eroded Vertisols, and (b) on severely eroded Cambisols.

(b) Phase of decreasing splash rates

On slightly eroded Lixisols and severely eroded Leptosols splash detachment rates decrease with time (figure 8.2).

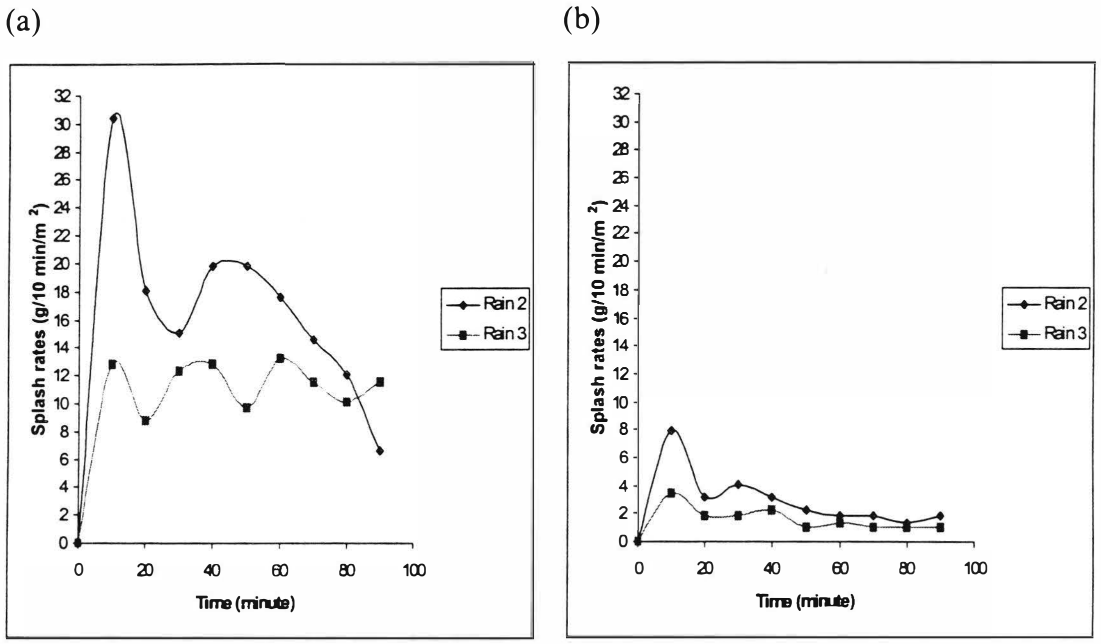


Figure 8.2 Temporal variations of splash erosion with decreasing splash detachment rates (a) on slightly eroded Lixisols, and (b) on severely eroded Leptosols.

Temporal decrease of splash rates is controlled by the availability of loose detachable soil particles or seal formation. Sediment wash and selective erosion change the particle size composition of the soil surface and lead to the formation of an erosion pavement, which diminishes the availability of loose detachable sediments. Seal formation may enhance the cohesion of soil particles and protects the aggregates below. Shaw (1929), Bryan (1973), Poesen and Savat (1978) and Parson (1994) show similar results. They relate the decrease of splash to the increasing depth of water at the soil surface, which partially disperses the detachment power of raindrop impact and hence decreases detachment by splash.

(c) Phase of constant splash rates

Despite an increase in rainfall intensity and duration, a phase of constant splash rates is observed on slightly and moderately eroded Planosols (figure 8.3). This indicates that the processes operating at the soil surface interact to reach an equilibrium between the resistance of the soil surface aggregates and the detachability power of the raindrops.

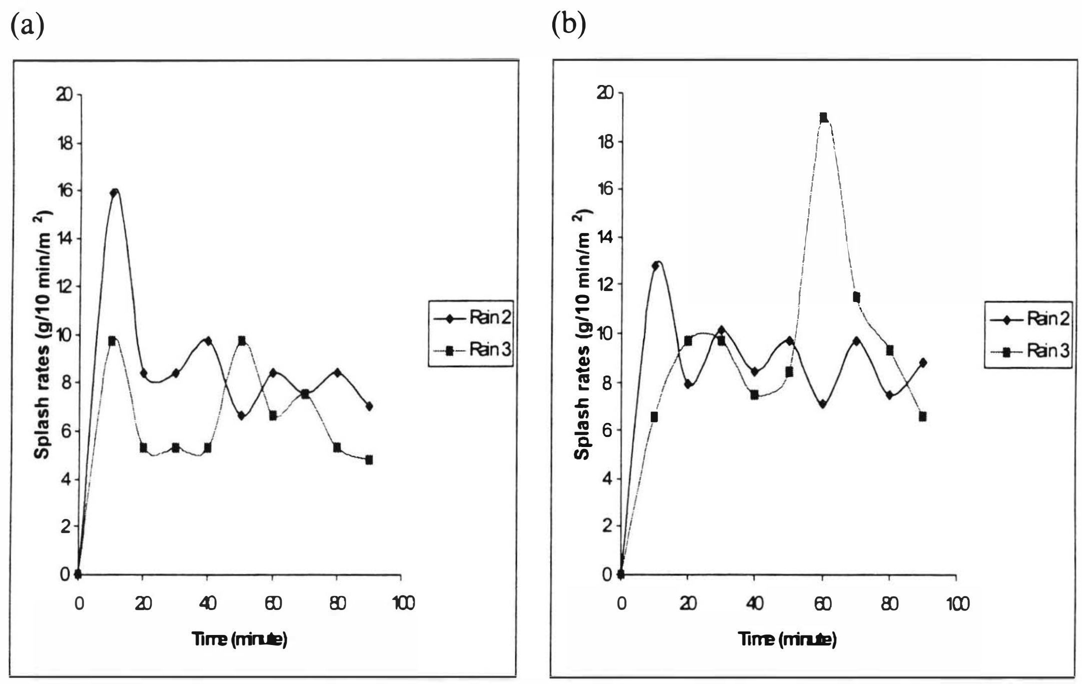


Figure 8.3 Temporal variations of splash erosion with constant splash detachment rates (a) on slightly eroded Planosols, and (b) on moderately eroded Planosols.

(2) Patterns of change in splash detachment

Throughout a rainfall event, many plots show a combination of all the three phases, others are characterized by only one or two phases, allowing to distinguish three patterns of splash erosion: one-phase pattern, double-phase pattern and complex pattern.

(a) One-phase pattern

A one-phase pattern shows a single dominant trend of either increasing, decreasing or constant splash detachment rates throughout the duration of a rain shower (figures 8.1, 8.2 and 8.3).

(b) Double-phase pattern

A double-phase pattern is composed of two different phases. Two types of double-phase pattern are identified: a convex-shape pattern and a concave-shape pattern. For instance, moderately eroded Cambisols have a convex-shape pattern consisting of a phase of increasing splash rates followed by a phase of decreasing splash rates (figure 8.4a). In contrast, concave-shape pattern consists of a phase of decreasing splash rates followed by a phase of increasing splash rates, as observed on moderately eroded Lixisols (figure 8.4b).

(a) (b)

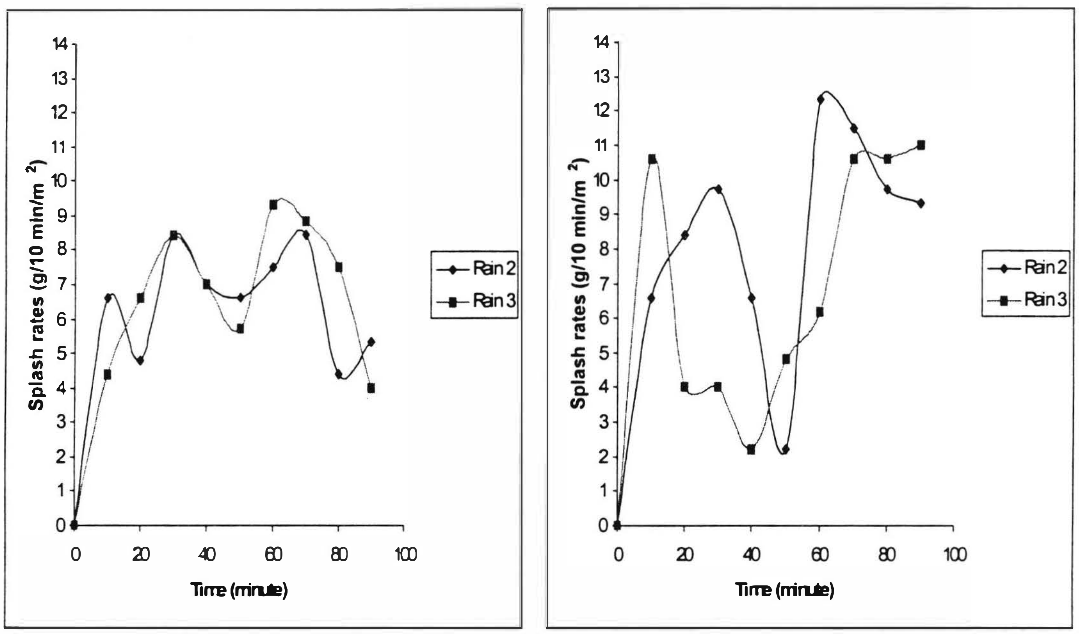


Figure 8.4 Temporal variations of splash erosion showing (a) convex pattern of splash detachment rates on moderately eroded Cambisols, and (b) concave pattern of splash detachment rates on moderately eroded Lixisols.

(c) Complex pattern

A complex pattern of splash detachment rates is found on many soils, such as on slightly eroded Fluvisols, slightly eroded Cambisols, severely eroded Lixisols, and severely eroded Planosols (figures 8.5 and 8.6). Splash erosion rates fluctuate throughout the duration of a rain shower. Phases of increasing, decreasing and constant splash rates develop but they are too short or mixed-up to be separated.

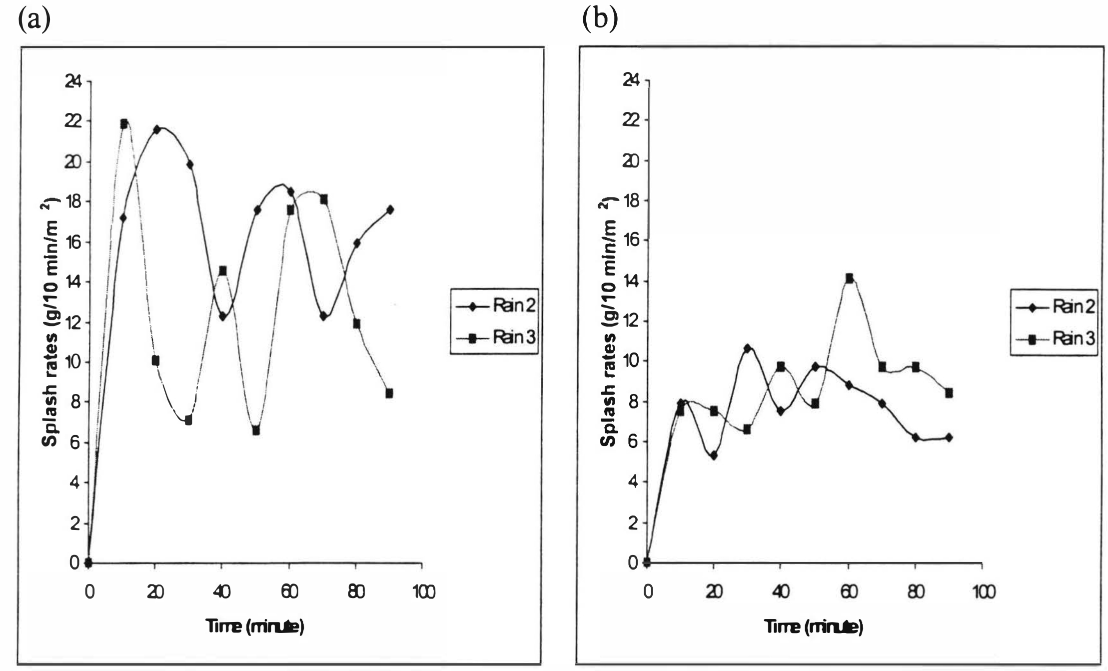


Figure 8.5 Temporal variations of splash erosion showing a fluctuation in splash detachment rates (a) on slightly eroded Fluvisols, and (b) on severely eroded Lixisols.

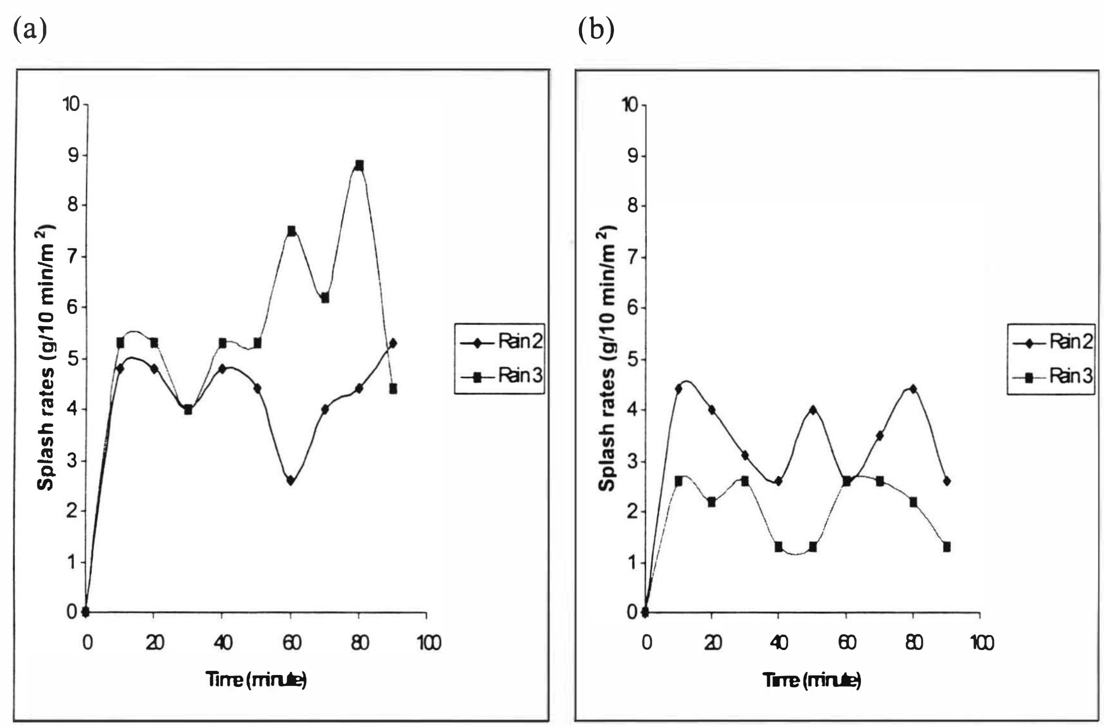


Figure 8.6 Temporal variations of splash erosion showing a fluctuation in splash detachment rates (a) on slightly eroded Cambisols, and (b) on severely eroded Planosols.

Fluctuating variations of splash detachment rates reveal that two processes operating in opposite directions may have taken place simultaneously at the soil surface. The first process is seal formation that consolidates the particle bonding forces, restricts infiltration and enhances overland flow. A thin layer of water at the soil surface absorbs part of the raindrop energy and reduces splash erosion. The second process is seal destruction by sheet erosion. In fact, as overland flow rises at the soil surface due to seal formation, the erosive power of the runoff increases and destroys the seal. Subsequently, water infiltrates along the cracks of the seal. At the same time, the water film at the soil surface decreases, and the soil surface aggregates are again exposed to raindrop impact, increasing splash detachment. Newly destroyed soil surface aggregates lead again to seal formation, and so on. Ellison (1945), Palmer (1963), Mutchler and Young (1975), Sloneker et al. (1976), Ghadiri and Payne (1981), Poesen (1981), Bradford et al. (1987), Torri et al. (1987), and Moore and Singer (1990) report similar results.

(3) Variations between rains

With increasing rain events, splash erosion might increase, decrease or remain constant (table 8.1). Ten plots, representing 40% of the experimental sites, show an increase in splashed sediment in rain 3. For instance, on slightly eroded Vertisols, the values of splashed sediment are 55 and 74 g/m^2 in rain 2 and rain 3, respectively. Similar behaviour is observed on slightly eroded Cambisols. In contrast, twelve plots representing 48% of the experimental sites exhibit a decrease in splashed sediment, despite an increase of rainfall intensity and duration in rain 3. On slightly eroded Lixisols, the values of splash erosion are 154 and 103 g/m^2 in rain 2 and rain 3, respectively. Likewise, slightly eroded Planosols and slightly eroded Fluvisols show a decrease of splash erosion between two consecutive rains. Lastly, the amounts of splashed sediment remained similar between the rains on only three plots (12%). For instance, on moderately eroded Lixisols (plot 18), the values of splashed sediment are 52 and 49 g/m^2 in rain 2 and rain 3, respectively.

Table 8.1 Erosion parameter values derived from the second rain and the third rain

Soil characteristics			Rain 2		Rain 3	
Soil types	**Erosion classes**	**Plot number**	**Splash (g/m^2)**	**Soil loss (g/m^2)**	**Splash (g/m^2)**	**Soil loss (g/m^2)**
Lixisols	slightly eroded	7	154	63	103	42
	moderately eroded	3	76	94	64	40
		4	42	22	91	88
		14	105	142	91	226
		18	52	55	49	34
		24	58	46	49	156
	severely eroded	16	70	61	81	329
		19	47	72	34	158
Vertisols	slightly eroded	6	55	0	74	0
	moderately eroded	11	81	39	54	48
		17	56	123	72	431
	severely eroded	21	40	28	59	613
Cambisols	slightly eroded	2	77	7	94	47
		23	39	0	52	33
	moderately eroded	10	60	37	34	62
		20	59	229	62	710
	severely eroded	1	65	59	106	157
		5	61	76	73	231
Fluvisols	slightly eroded	9	153	57	117	82
	moderately eroded	22	123	28	93	46
Leptosols	severely eroded	12	27	38	15	48
Planosols	slightly eroded	15	80	92	60	220
	moderately eroded	13	82	66	88	179
	severely eroded	8	35	107	40	153
		25	31	160	19	409

The differences in splash detachment rates between two consecutive rain showers result from changes in rainfall characteristics, antecedent soil moisture content, cohesion of the soil surface aggregates and particle size composition of the topsoil layer. Parson et al. (1990) report similar behavior.

8.1.2 Variations between soil types

Total splash sediment production rates for selected soils were compared. Relative susceptibility to splash detachment varies according to erosion classes (figure 8.7). Considering the splash erosion during the third rain, the order of increasing relative susceptibility to splash detachment is: (1) Cambisols < Planosols < Vertisols <Lixisols on slightly eroded soils; (2) Lixisols < Cambisols < Vertisols < Planosols on moderately eroded soils; and (3) Planosols << Vertisols < Lixisols < Cambisols on severely eroded soils

(a) (b)

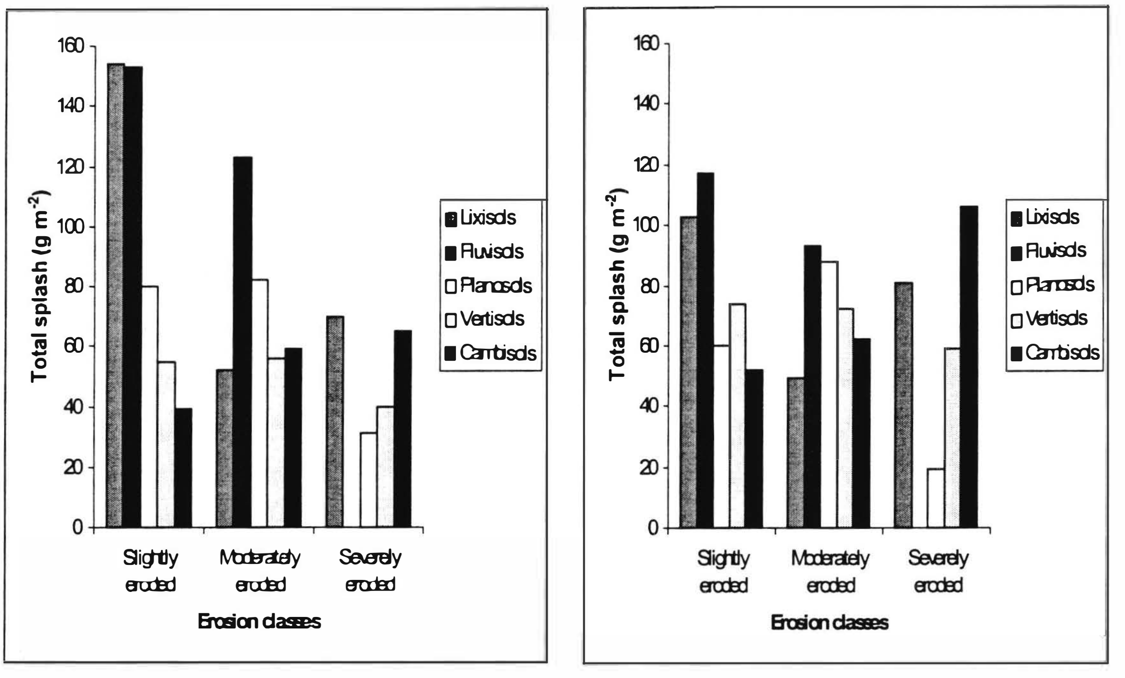


Figure 8.7 Total splash sediment production rates on different erosion types of the selected major soil types in the second rain (a) and the third rain (b).

8.1.3 Variations between erosion classes

As expected, erosion classes show differences in splash erosion. On Lixisols (figure 8.8), the order of increasing relative susceptibility to splash detachment for both rains is: moderately eroded < severely eroded < slightly eroded. But on Vertisols (figure 8.9) and Fluvisols (figure 8.10), the order is: severely eroded < moderately eroded < slightly eroded. On Planosols (figure 8.11) the order is: severely eroded << slightly eroded < moderately eroded. On Cambisols (figure 8.12) the order is: slightly eroded < moderately eroded < severely eroded.

(a) (b)

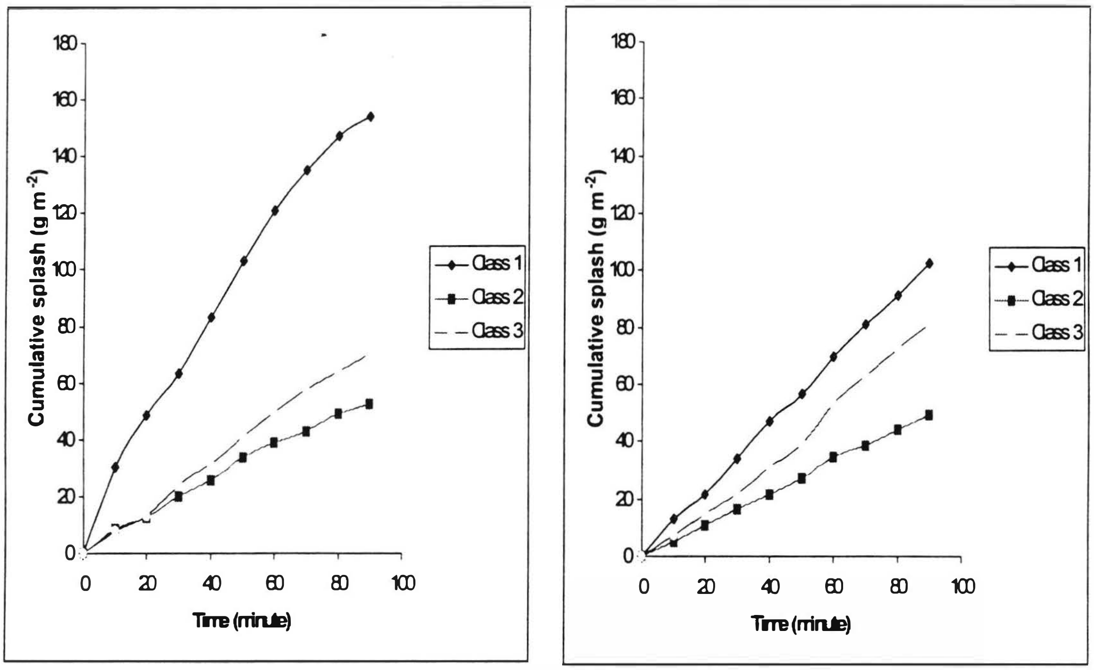


Figure 8.8 Cumulative splash erosion on slightly eroded Lixisols (class 1), moderately eroded Lixisols (class 2) and severely eroded Lixisols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

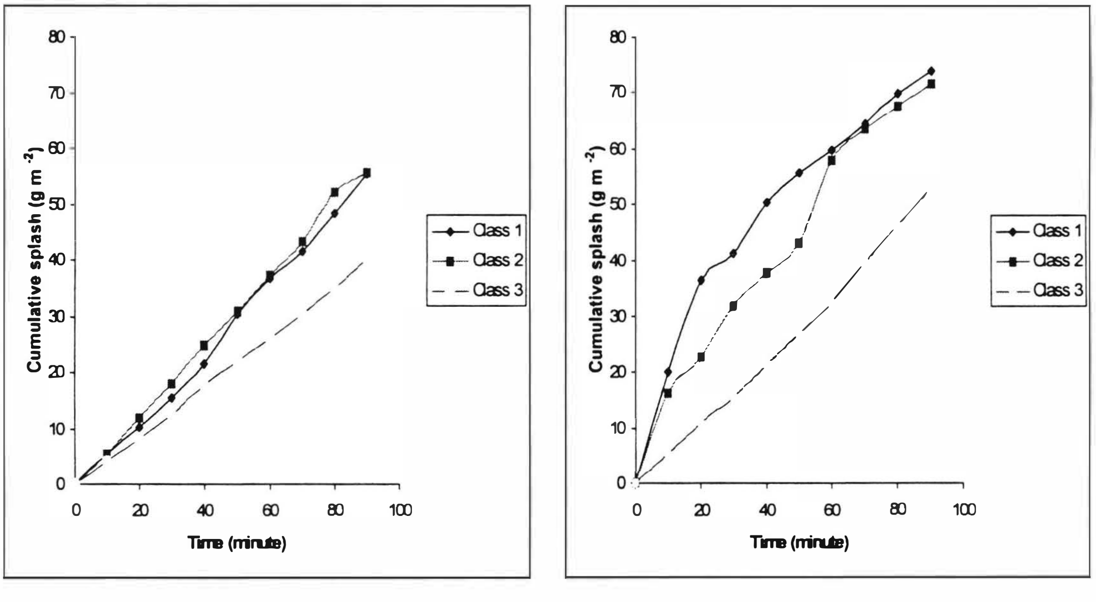


Figure 8.9 Cumulative splash erosion on slightly eroded Vertisols (class 1), moderately eroded Vertisols (class 2) and severely eroded Vertisols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

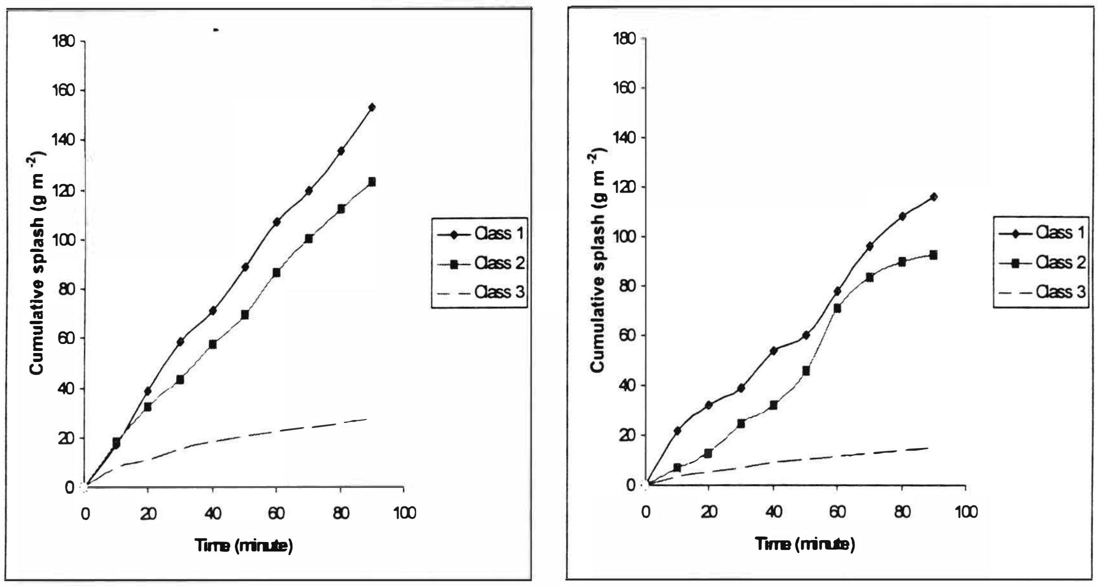


Figure 8.10 Cumulative splash erosion on slightly eroded Fluvisols (class 1), moderately eroded Fluvisols (class 2) and severely eroded Leptosols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

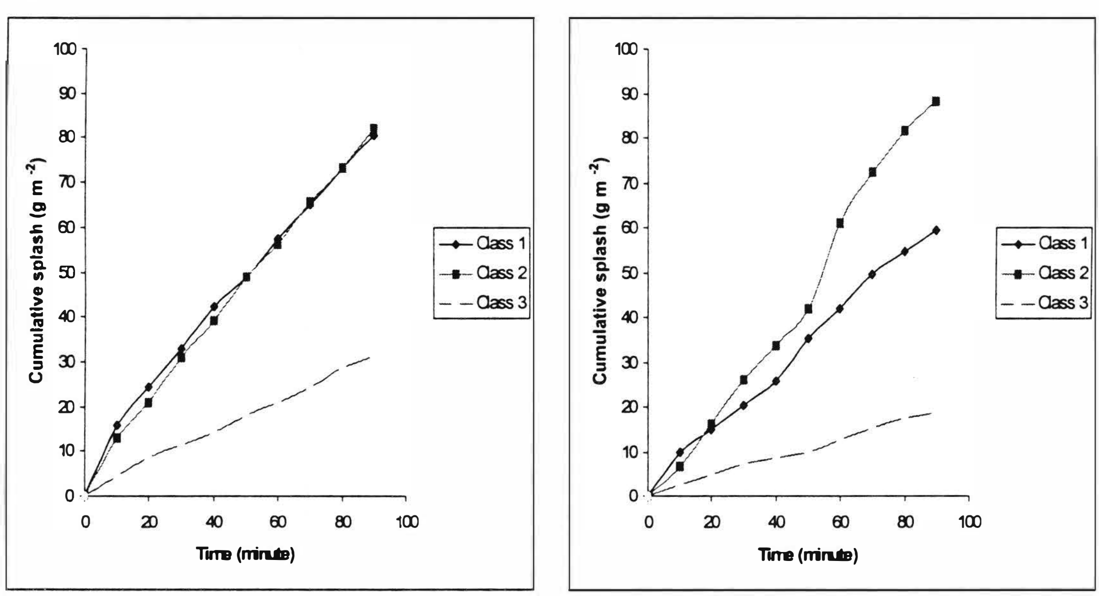


Figure 8.11 Cumulative splash erosion on slightly eroded Planosols (class 1), moderately eroded Planosols (class 2) and severely eroded Planosols (class 3) in the second rain (a) and the third rain (b).

(a) (b)

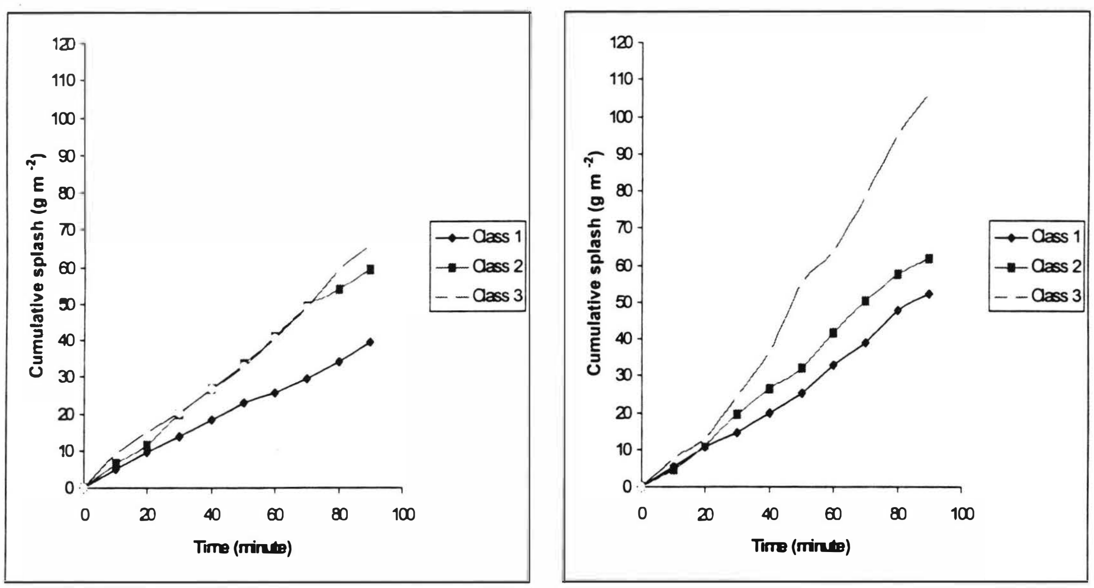


Figure 8.12 Cumulative splash erosion on slightly eroded Cambisols (class 1), moderately eroded Cambisols (class 2) and severely eroded Cambisols (class 3) in the second rain (a) and the third rain (b).

Differential behaviour between erosion classes can be attributed to changes in particle size composition and loss organic matter in the soil surface aggregates due to erosion. For instance, on Lixisols, Vertisols and Planosols, the texture of the topsoil layer is finer (clay) with increasing erosion severity. Fine soil particles are easily detachable. Additionally, decreased organic matter content due to erosion decreases soil cohesion, which promotes soil particle detachability. In contrast, on Cambisols, the texture of the topsoil layer is coarser with increasing erosion severity. Coarse particles resist raindrop impact.

8.2 INTERRILL SOIL LOSS

8.2.1 Changes over time

(1) Variations of the sediment delivery pattern within rainfall events

The examination of temporal variations in the sediment delivery throughout a rainfall event permits to distinguish globally three outcome situations with respect to sediment concentration in the runoff: sediment concentration may increase, decrease or remain constant over time. In each situation, high or low outliner values may appear, but they do not modify the general trend of the sediment delivery. Many plots show a combination of all the three phases in each simulated rain; others have simple behaviour. Two main patterns were identified: a one-phase pattern and a complex pattern.

(a) One-phase pattern

A one-phase pattern corresponds to a single behavior in the sediment delivery process over the duration of a rain shower. Three types of one-phase pattern are found: increasing trend, decreasing trend and constant trend in the variations of sediment concentration. For instance, the sediment concentration increases on severely eroded Planosols and severely eroded Vertisols (figure 8.13). Slightly and moderately eroded Lixisols show a decrease of sediment concentration (figure 8.14), whereas the sediment concentration remains constant on severely eroded Leptosols and severely eroded Lixisols (figure 8.15).

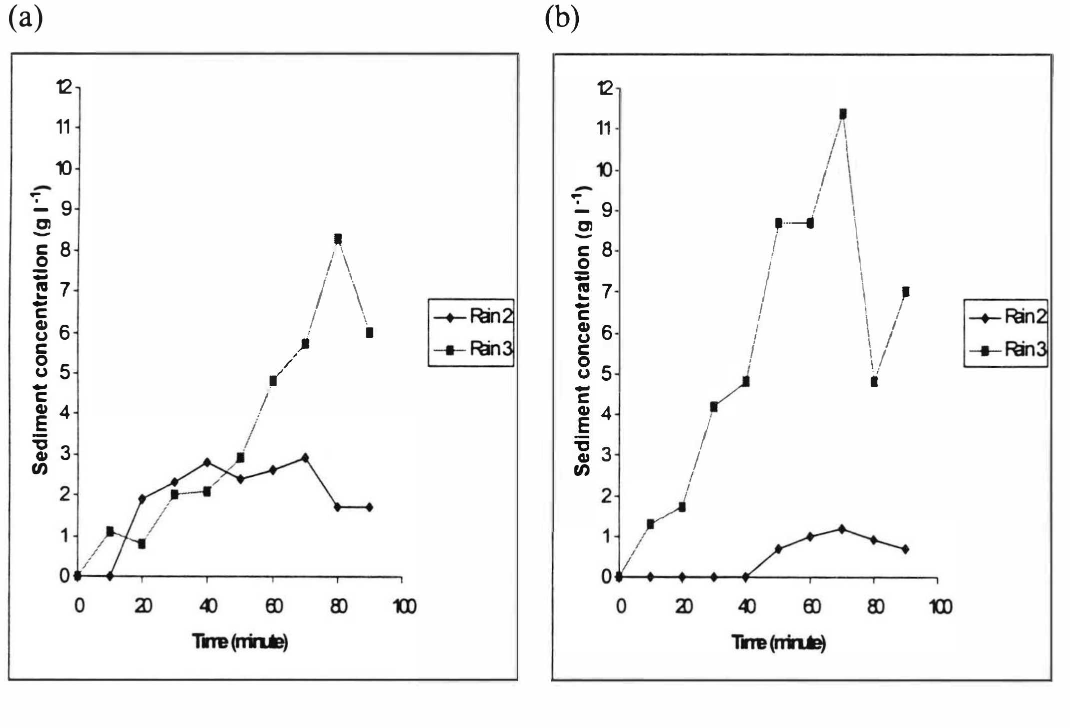
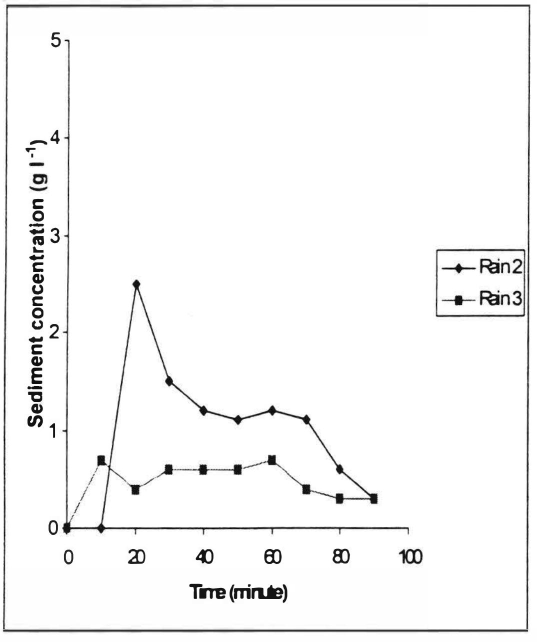


Figure 8.13 Temporal variations of sediment concentration in runoff, with increasing trend of interrill soil loss (a) on severely eroded Planosols, and (b) on severely eroded Vertisols.

(a)



(b)

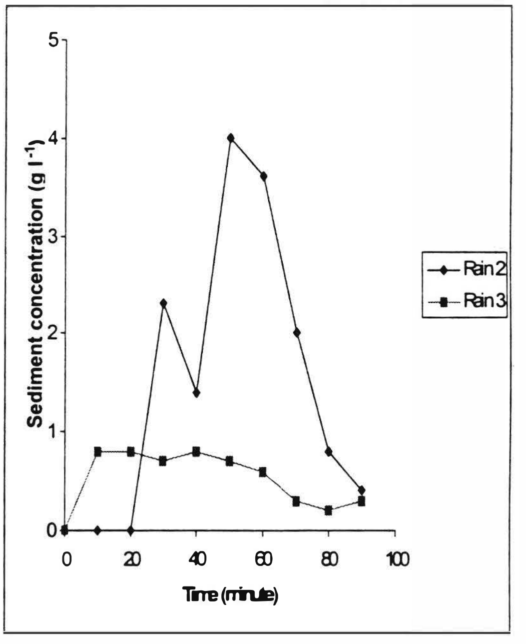
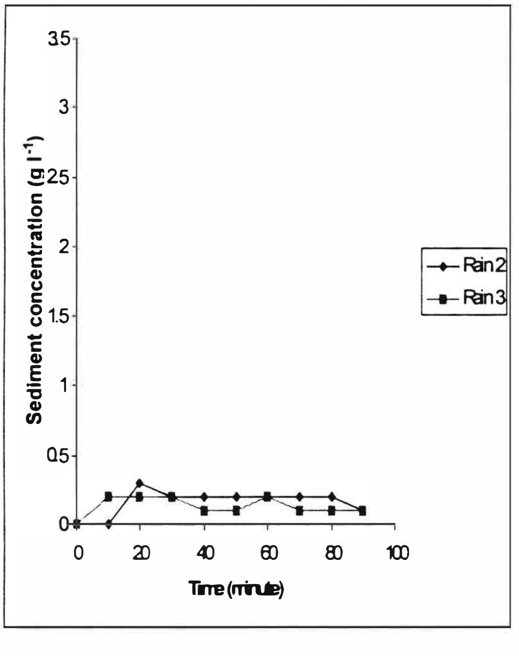


Figure 8.14 Temporal variations of sediment concentration in runoff, with decreasing trend of interrill soil loss (a) on slightly eroded Lixisols, and (b) on moderately eroded Lixisols.

(a)



(b)

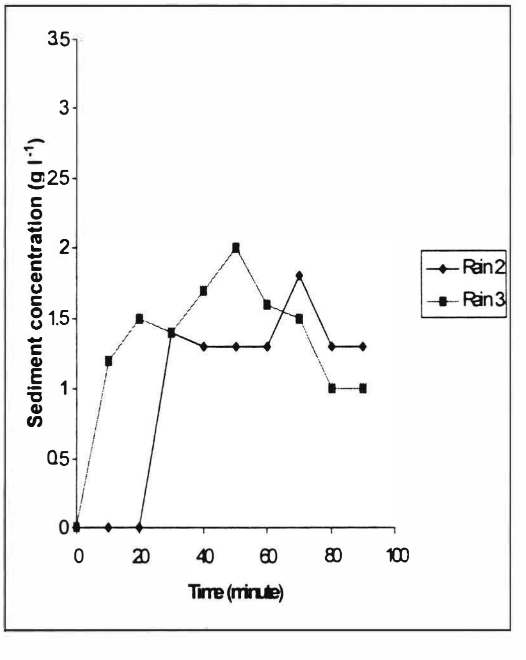


Figure 8.15 Temporal variations of sediment concentration in runoff, with constant trend of interrill soil loss (a) on severely eroded Leptosols, and (b) on severely eroded Lixisols.

(b) Complex pattern

A complex pattern is created when several phases of variations in sediment concentration occur throughout a rainfall event. For instance, moderately eroded Cambisols and moderately eroded Vertisols exhibit a convex-shaped pattern, where sediment concentration in the runoff first increases, then decreases (figure 8.16). On slightly eroded Fluvisols and severely eroded Cambisols, the pattern of sediment concentration fluctuates throughout the duration of a shower (figure 8.17). Phases of increasing, decreasing and constant sediment delivery may be found, but they are too short or intermingled to be separated.

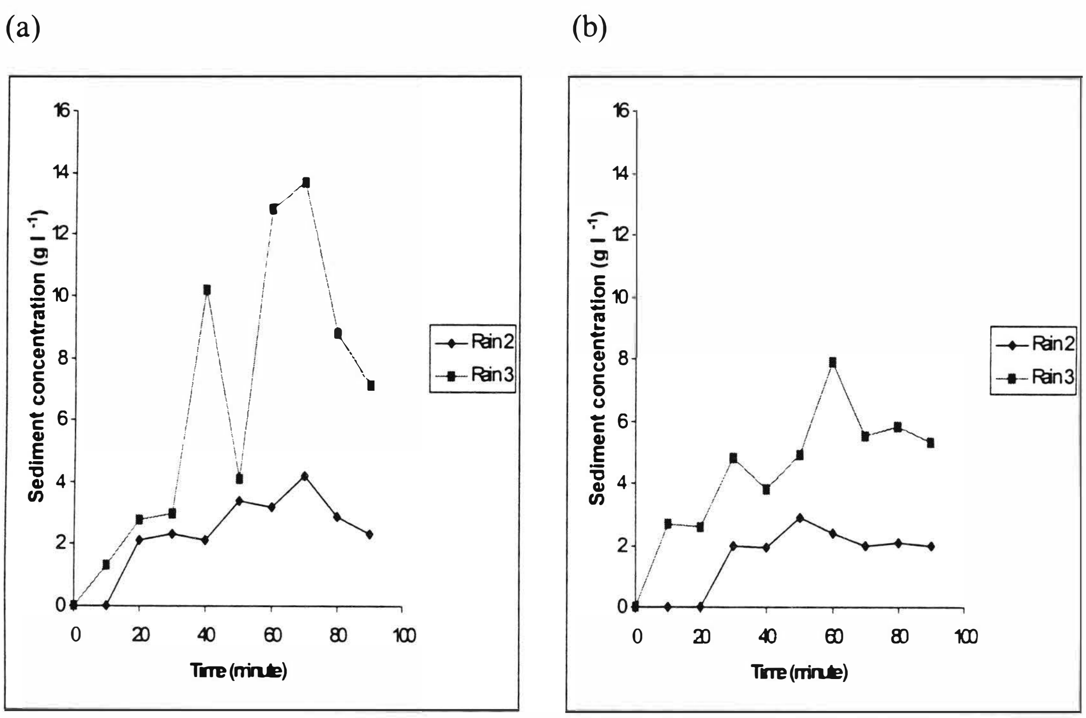


Figure 8.16 Temporal variations of sediment concentration in runoff, showing convex-shaped pattern of interrill soil loss (a) on moderately eroded Cambisols, and (b) on moderately eroded Vertisols.

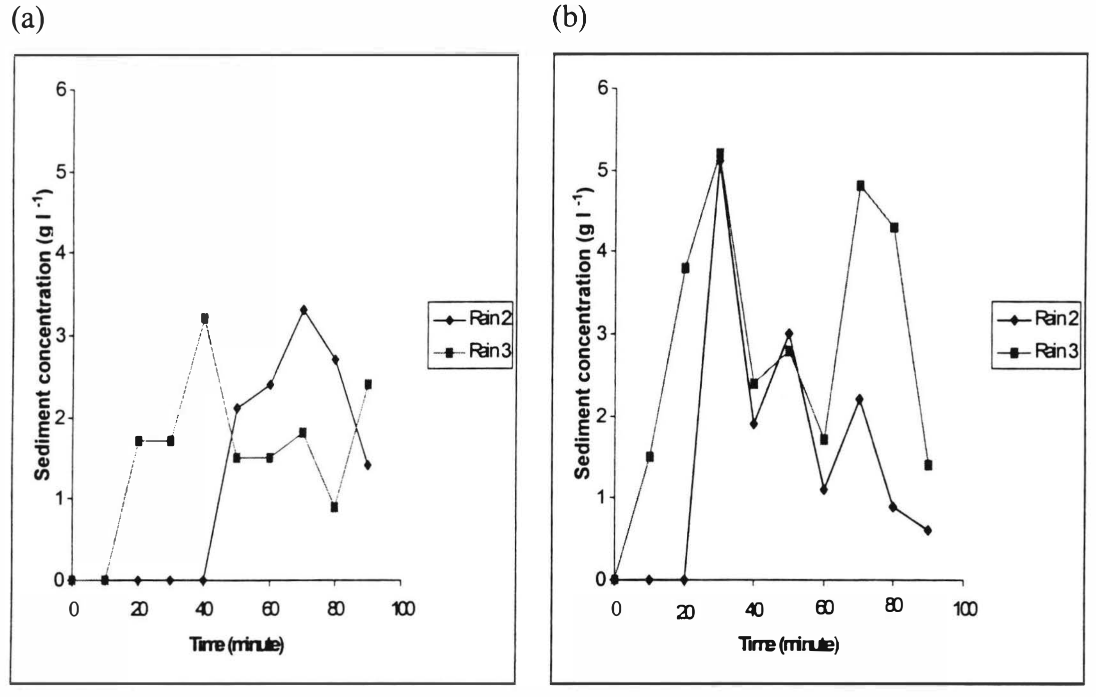


Figure 8.17 Temporal variations of sediment concentration in runoff, showing fluctuations of interrill soil loss (a) on slightly eroded Fluvisols, and (b) on severely eroded Cambisols.

The variations in sediment concentration within a rainfall can be attributed to the processes controlling splash detachment rates, such as seal formation, seal destruction and formation of a thin layer of water at the soil surface, discussed above.

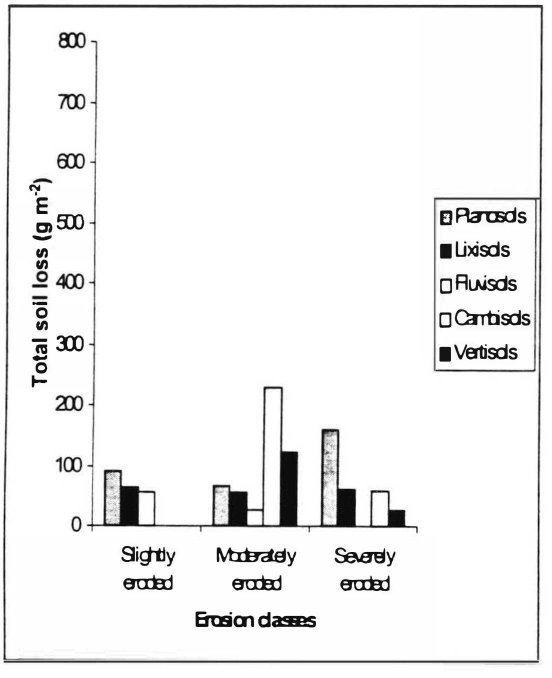
(2) Variations between rains

Interrill soil loss between rains may increase, decrease or remain constant. Most of the experimental plots on all erosion classes of Fluvisols, Cambisols and Planosols, moderately and severely eroded Vertisols, and severely eroded Lixisols, show an increase in soil loss with time. As rainfall intensity and duration increase from the second to the third rain, there is a positive correlation between erosion and rainfall characteristics. Substantial increase in soil loss was found particularly on moderately eroded Cambisols, severely eroded Vertisols, severely eroded Planosols and severely eroded Lixisols. The values of soil loss are 229, 123, 160 and 61g/m^2 in the second rain, but increase to 710, 613, 409 and 329 g/m^2 in the third rain, respectively (table 8.1). In contrast, some soils such as slightly and moderately eroded Lixisols show a decrease in soil loss, despite a substantial increase in rainfall characteristics. The values of soil loss are 63 and 55 g/m^2 in the second rain, but they are 47 and 34 g/m^2 in the third rain, respectively. This negative correlation may be attributed to selective erosion and concentration of coarse material on the soil surface or to diminishing roughness and progressive crusting. Slightly eroded Vertisols did not produce soil loss.

8.2.2 Variations between soil types

The order of increasing relative susceptibility to erosion of the soil types changes according to erosion classes (figure 8.18).

(a)



(b)

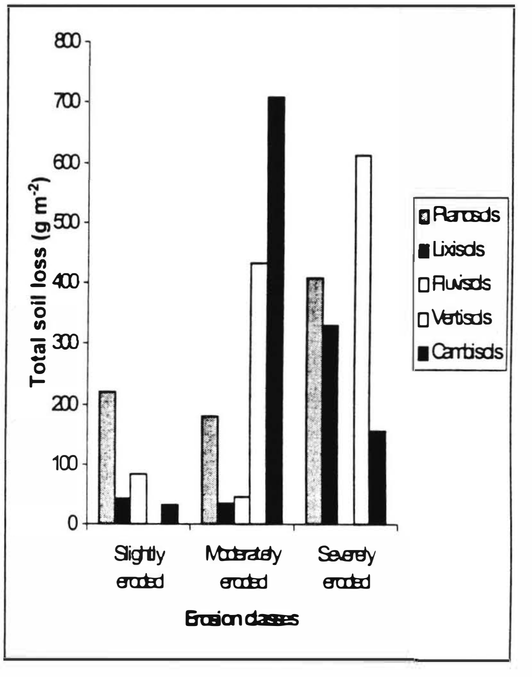


Figure 8.18 Total soil loss on different erosion classes of the selected soil types in the second rain (a) and the third rain (b).

Considering only the soil losses caused by the third rain, the order is: (1) Vertisols < Cambisols < Lixisols < Fluvisols << Planosols on slightly eroded soils; (2) Fluvisols < Lixisols < Planosols < Vertisols < Cambisols on moderately eroded soils; and (3) Fluvisols < Cambisols < Lixisols < Planosols < Vertisols on severely eroded soils. Thebe (1987), Seiny (1990) and Mahop et al. (1995) report similar results.

Behaviour is determined by differences in soil properties, in particular those properties that control permeability and regulate infiltration and percolation. On Vertisols for instance, cracks absorb the rain water, and it is only after closing of the cracks that runoff starts. The horizon sequence in Lixisols and Planosols includes coarse-textured topsoil layers (Ap and A2) above heavy, hard and structureless subsoil layers (Btd and Bt). Permeability and runoff depend on the least permeable horizon in the layer sequence. Bt horizons promote saturation overland flow (De Ploey, 1986; Kuipers, 1986). Contrasting layers result in higher runoff production, which contributes to the deterioration of the surface structure and the structural stability.

Soil containing rock fragments, as it is the case for some eroded Lixisols, are more susceptible to soil loss through selective erosion. Also a large rock fragment cover on the soil surface increases rock flow discharge, causing more runoff and soil loss. Fletcher and Bentner (1941), Poesen and Lavee (1991) and Bunte and Poesen (1994) report similar behavior. The small soil loss obtained on crusted topsoils of slightly and moderately eroded Lixisols is related to the cementing action of crust formation, that enhances soil cohesion and reduces soil detachment.

8.2.3 Variations between erosion classes

As expected, established erosion classes show also differences in interrill soil erosion. On Lixisols (figure 8.19) and Vertisols (figure 8.20), the order of increasing relative susceptibility to erosion in the third rain is indicated by: slightly eroded < moderately eroded < severely eroded. On Planosols (figure 8.21) the order is: moderately eroded < slightly eroded < severely eroded. It is: slightly eroded < severely eroded < moderately eroded on Cambisols (figure 8.22). Slightly eroded and moderately eroded Fluvisols show similar susceptibility to erosion (figure 8.23).

(a) (b)

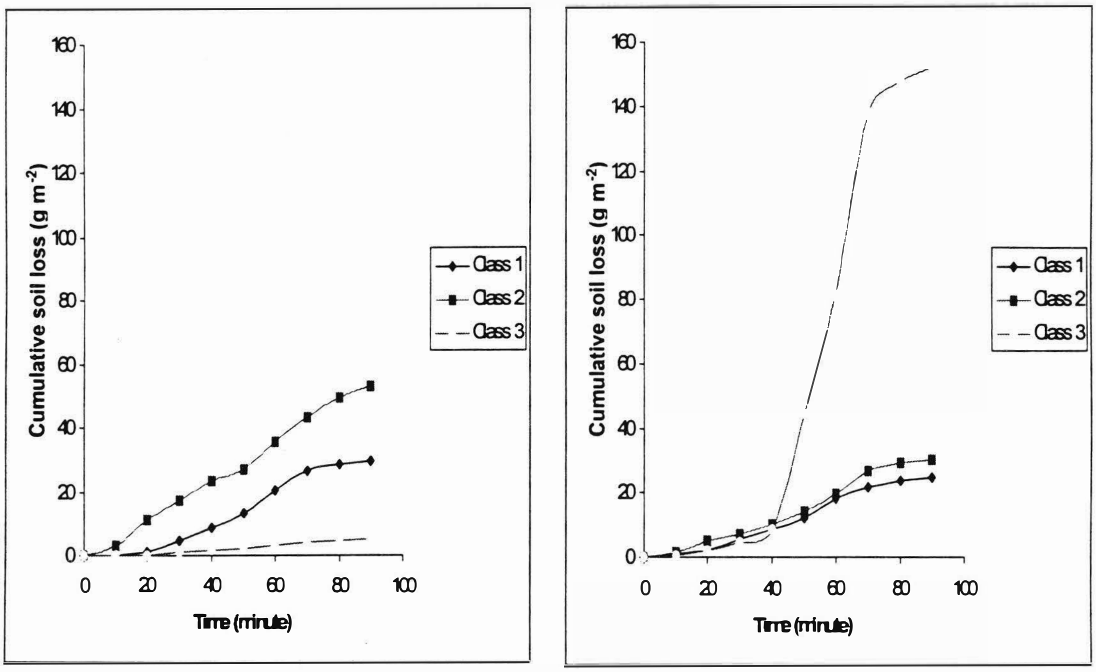


Figure 8.19 Cumulative soil loss on slightly eroded Lixisols (class 1), moderately eroded Lixisols (class 2) and severely eroded Lixisols (class 3) in the second rain (a) and third rain (b).

(a) (b)

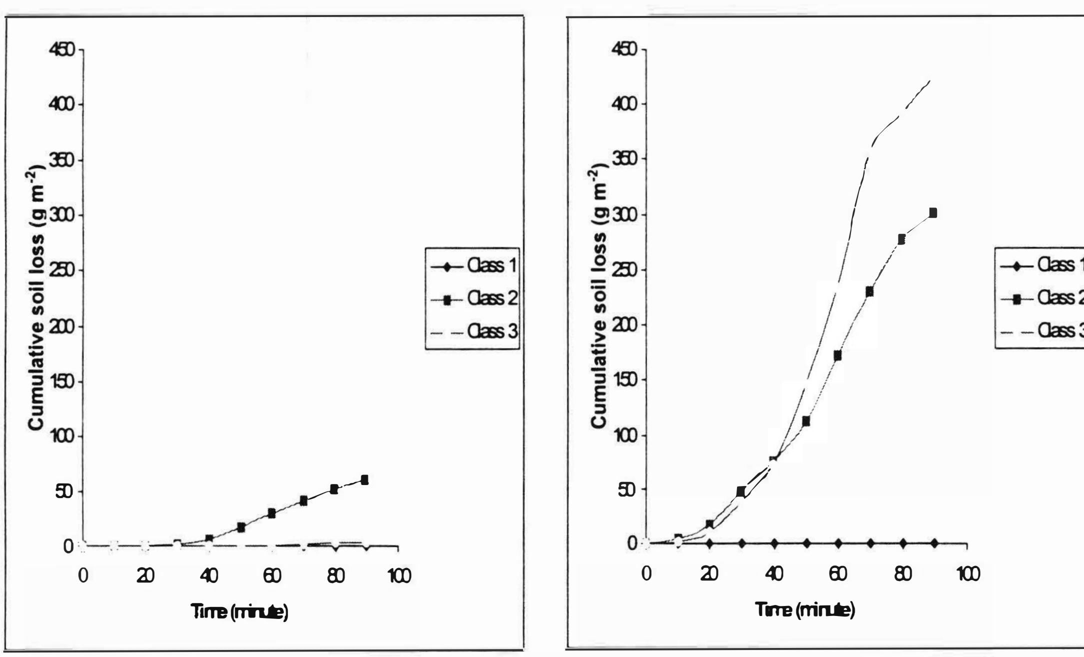


Figure 8.20 Cumulative soil loss on slightly eroded Vertisols (class 1), moderately eroded Vertisols (class 2) and severely eroded Vertisols (class 3) in the second rain (a) and third rain (b).

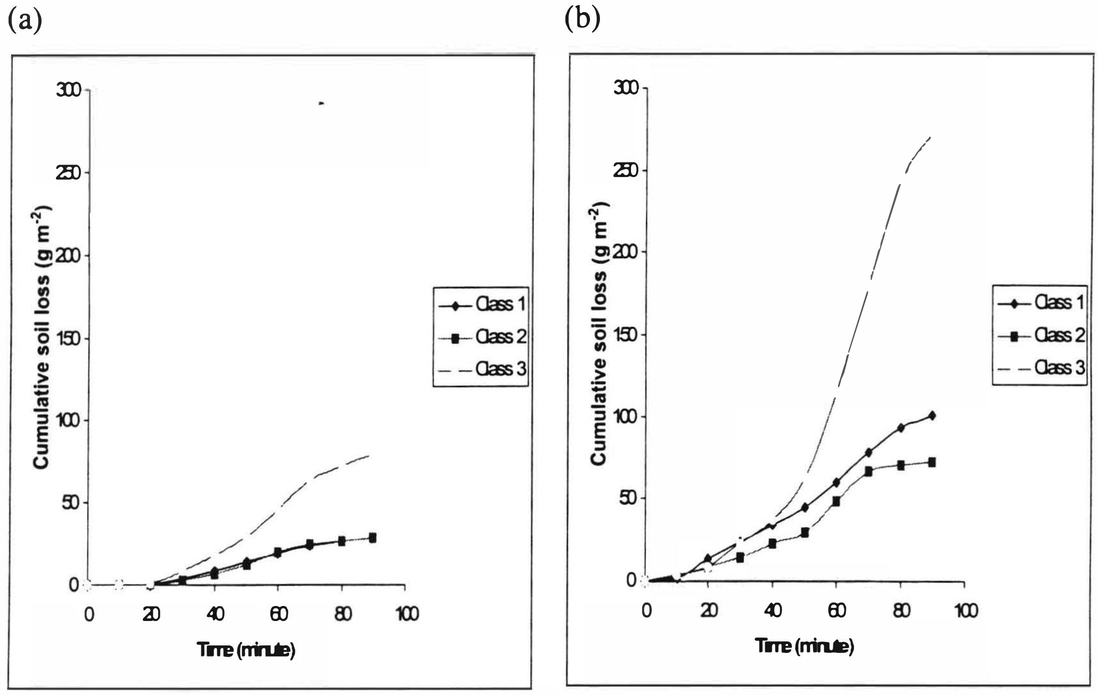


Figure 8.21 Cumulative soil loss on slightly eroded Planosols (class 1), moderately eroded Planosols (class 2) and severely eroded Planosols (class 3) in the second rain (a) and third rain (b).

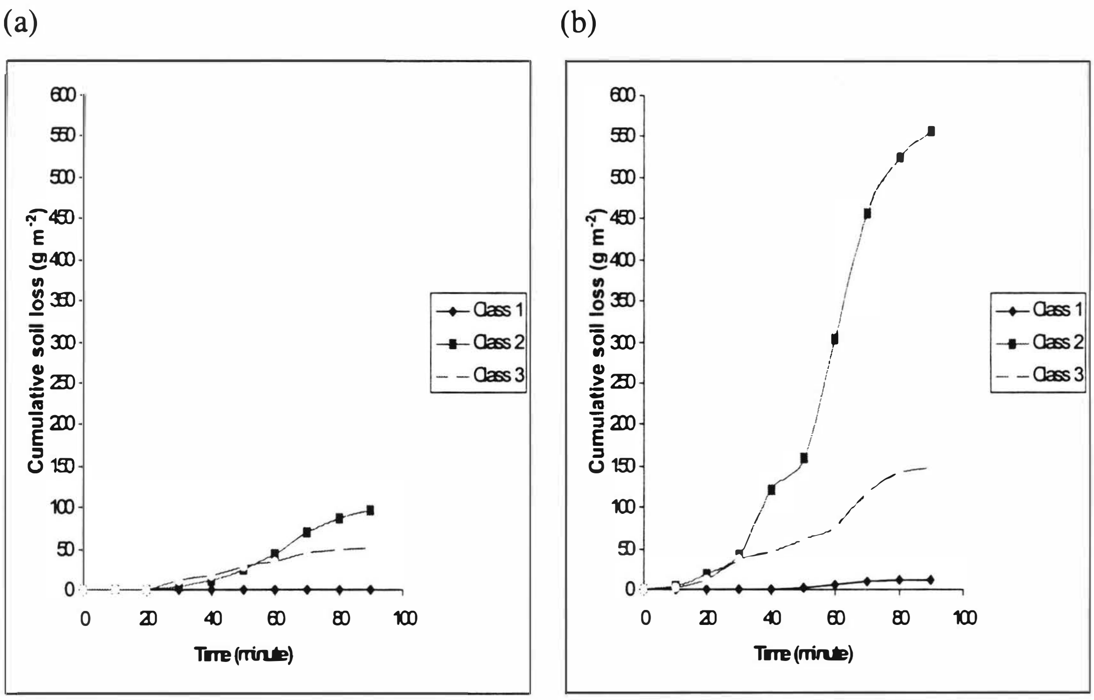


Figure 8.22 Cumulative soil loss on slightly eroded Cambisols (class 1), moderately eroded Cambisols (class 2) and severely eroded Cambisols (class 3) in the second rain (a) and third rain (b).

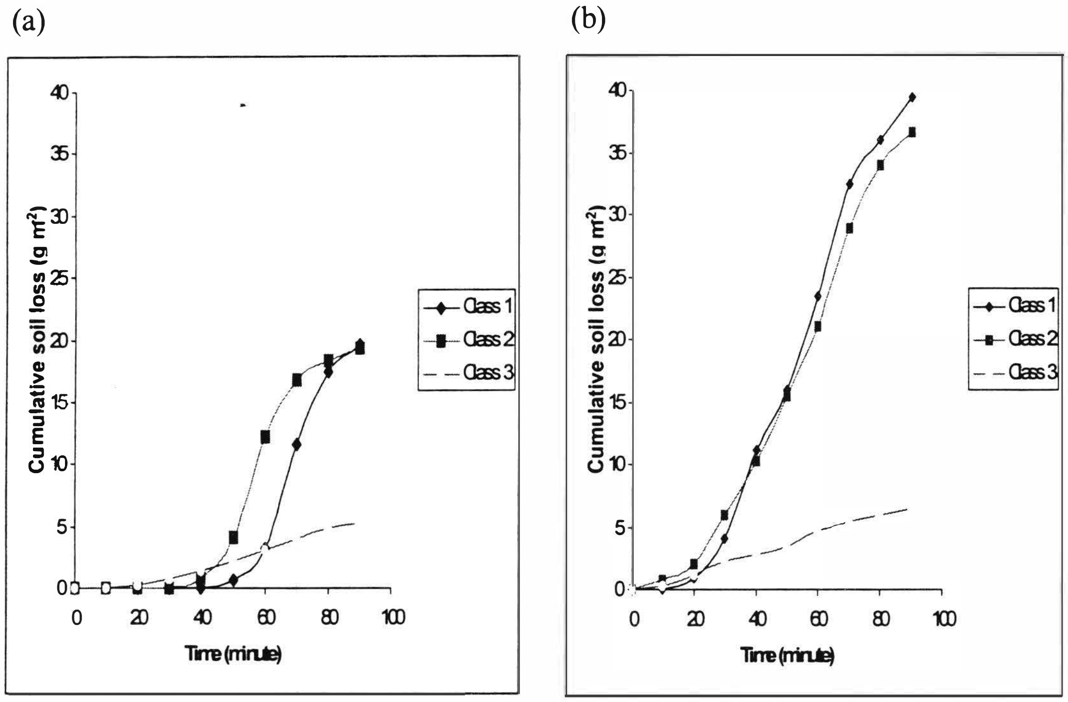


Figure 8.23 Cumulative soil loss on slightly eroded Fluvisols (class 1), moderately eroded Fluvisols (class 2) and severely eroded Leptosols (class 3) in the second rain (a) and third rain (b).

The general tendency is that soil already eroded keep on producing more erosion. This may vary over considerable ranges, such as on Vertisols where no soil loss was observed on slightly eroded soils, but 642 g/m^2 of soil loss was measured on severely eroded soils. Likewise, on Cambisols values of 33 g/m^2 and 939 g/m^2 of soil loss were measured on slightly eroded soils and moderately eroded soils, respectively. Thebe (1987), Seiny (1990) and Mahop et al. (1995) report similar orders of magnitude.

The differential behavior of the erosion classes can be attributed to modifications in the topsoil characteristics, such as clay and organic matter contents, and the thickness of the topsoil layers according to erosion degrees (Lal, 1988). More eroded soils (Lixisols and Planosols) have a higher clay content (>20 %) in the surface horizons than less eroded ones. A higher clay content promotes stronger cohesion of the soil surface aggregates, which resist slaking. Resistant clods maintain the depression storage, enhance infiltration and retard erosion. But as the rain proceeds, saturation overland flow occurs and the apparent resistance of eroded soils to runoff and erosion decreases consistently. On moderately and severely eroded Vertisols, cracks are less efficient in absorbing water. In contrast, less eroded soils present thicker topsoil layers (>15 cm) and a higher organic matter content (0.5-1%) than more eroded ones, providing larger water storage capacity.

8.3 CONCLUSION

The susceptibility of the soils to erosion changes according to soil types. The order of increasing relative susceptibility to erosion is indicated by: slightly eroded Vertisols < slightly eroded Cambisols < slightly and moderately eroded Lixisols < slightly and moderately eroded Planosols < severely eroded Lixisols < severely eroded Planosols, moderately and severely eroded Vertisols < severely eroded Cambisols. The differential behaviour between the erosion classes can be attributed to the modifications that affect the topsoil characteristics, such as clay and organic matter contents, and the thickness of the topsoil layers according to erosion degrees. Behaviour differences among soil types are controlled by differences in soil properties that control permeability and regulate infiltration and percolation. These results agree with those found by Pontanier et al. (1984), Thebe (1987), Seiny (1990) and Mahop et al. (1995). Additionally, the present investigation emphasizes the variations in splash erosion, which allows the partitioning of interrill erosion in terms of sources of soil loss (chapter 10).

CHAPTER 9

SOIL EROSION INDICATORS

At micro-plot level, twenty five sites, representing the regional soil types with different erosion classes, were subjected to artificial rainfall. Three erosion classes were identified, including (1) slightly eroded soils, (2) moderately eroded soils, and (3) severely eroded soils. Three rain showers were simulated at different intensities and durations on one-square-meter plots. Plots were bare and ploughed with a hand hoe. Soil surface roughness was assessed by measuring surface elevation points with a ruler, from a baseline reference downwards to the soil surface, along transects 5 cm apart, on 1m by 1m plots. A first rain (rain 1) was applied to the bare soil surface and, after hand-ploughing, the arable microtopography was recorded. Elevation points were measured after each of the two consecutive rains (rain 2 and rain 3). Variations of the soil surface elevation points between ploughing and rain 2 and between rain 2 and rain 3 on each experimental plot were compared to describe the interactions between rainfall characteristics, runoff, soil loss and soil surface microrelief.

At plot level, two sites, one on moderately eroded Lixisols and the other on moderately eroded Vertisols, were selected. On each of the two soils, an area of 40 m x 104 m was delineated from the divide downslope. The general slope was 1% at each experimental site. Both areas had similar topographic characteristics (position, slope length and slope steepness). Erosion features and related incidental features, such as crop characteristics, were recorded on a grid at 8 m intervals between observation points. Cotton was cultivated on moderately eroded Lixisols, whereas Mouskwari sorghum was cultivated on moderately eroded Vertisols. The location of critical erosion indicators was recorded, allowing to design initial measures for soil and water conservation.

9.1 VARIATIONS OF THE SOIL EROSION INDICATORS AT MICRO-PLOT SCALE

9.1.1 Variations of the soil surface elevation points with rains

The soil surface elevation points might show substantial decrease, moderate decrease, small decrease or substantial increase with increasing rainfall, in terms of number of events, duration and intensity. Three patterns of change were between ploughing and rain 2, and between rain 2 and rain 3, respectively. The first pattern is characterized by moderate decrease followed by moderate decrease of the elevation points. The second pattern consists of substantial decrease followed by small decrease of the elevation points. The last pattern exhibits moderate decrease followed by substantial increase of the elevation points (table 9.1).

Table 9.1 Soil surface elevation point characteristics (values in mm)

Soil types	Erosion classes	Plot n_o	Treatment	Mean	Standard deviation	Elevation difference	
						a - b	b – c
Lixisols	Slightly eroded	7	a b c	151 141 140	7.5 6.3 6.6	10	1
	Moderately eroded	3	a b c	171 160 158	11.6 7.9 7.0	11	2
		4	a b c	172 166 165	12.8 11.9 9.6	6	1
		14	a b c	185 175 171	11.7 8.7 8.0	10	4
		18	a b c	156 149 148	9.5 5.6 5.9	7	1
		24	a b c	166 163 162	11.6 7.9 5.6	3	1
	Severely eroded	16	a b c	188 186 183	8.4 10.9 12.8	2	3
		19	a b c	164 162 161	9.8 9.3 6.7	2	1
Vertisols	slightly eroded	6	a b c	171 169 179	16.9 15.7 19.5	2	-10
	Moderately eroded	11	a b c	176 163 162	12.1 8.7 7.5	13	1
		17	a b c	165 164 162	11.0 8.8 6.0	1	2
	Severely eroded	21	a b c	176 175 173	12.6 12.9 9.7	1	2

Table 9.1 (continued)

Soil types	Erosion classes	Plot n_o	Treatment	Mean	Standard deviation	Elevation difference a - b	Elevation difference b - c
Cambisols	Slightly eroded	2	a b c	168 162 160	9.2 8.2 7.3	6	2
		23	a b c	165 166 167	10.3 10.9 10.9	-1	-1
	Moderately eroded	10	a b c	176 164 163	8.6 6.5 5.9	12	1
		20	a b c	177 175 171	13.7 9.6 7.7	2	4
	Severely eroded	1	a b c	153 144 143	9.3 7.7 7.5	9	1
		5	a b c	176 166 163	11.3 9.4 8.6	10	3
Fluvisols	Slightly eroded	9	a b c	187 175 174	11.0 9.5 8.6	12	1
	Moderately eroded	22	a b c	161 159 158	6.5 4.4 3.9	2	1
Leptosols	Severely eroded	12	a b c	159 155 154	7.9 6.5 5.6	4	1
Planosols	Slightly eroded	15	a b c	180 167 166	10.2 7.4 5.8	13	1
	Moderately eroded	13	a b c	154 153 151	6.8 5.2 4.7	1	2
	Severely eroded	8(*)	a b c	-	-	-	-
		25	a b c	179 174 173	9.0 6.7 6.9	5	1

a = surface elevation after ploughing; b = surface elevation after rain 2; c = surface elevation after rain 3; Mean = mean elevation; (*) = defected.

Each new microtopographic configuration is strongly related to the relative strength of the soil surface aggregates.

(1) Moderate decrease followed by moderate decrease of the soil surface elevation points: eroding soil surface aggregates

During rain 2 and rain 3, a moderate decrease of the soil surface elevation points with time, accompanied by a substantial soil loss, was observed on severely eroded Lixisols. The positive correlation between the decrease of the elevation points and the amount of rain reflects a very eroding soil surface condition. Standard deviation is relatively high, indicating large variation of the elevation points due to selective erosion areas. Moderately and severely eroded Vertisols and Planosols show similar behavior.

(2) Substantial decrease followed by small decrease of the soil surface elevation points: moderately resisting soil surface aggregates

A substantial decrease of the elevation points, but accompanied by relatively low soil loss, was observed on slightly eroded Lixisols and slightly eroded Planosols after application of rain 2. This denotes that most sediment has been redistributed over the plot and did not reach the plot outlet. Despite a greater amount of water applied in rain 3, the elevation of the points on slightly eroded Lixisols and all erosion classes of Planosols did not decrease significantly. This may indicate that a flattening of the soil surface, accompanied by crusting, has taken place during the previous rain. Standard deviation decreases to relatively low values between consecutive rains, reflecting a uniform removal of soil material at the terrain surface. Lower soil loss is evidence of crust formation, which tends to inhibit soil detachment. Similar behavior has been reported by Levy et al. (1994).

(3) Moderate decrease followed by substantial increase of the soil surface elevation points: resisting soil surface aggregates

On slightly eroded Vertisols, the application of rains causes an increase of the elevation points, reflecting the presence of swelling clays (smectites). Dry clods absorb water, which causes their expansion. Swelling clods may promote resisting soil surface. This trend can also be traced on moderately and severely eroded Vertisols, where only small changes affect the elevation points between rains.

The variation of the soil surface elevation points with increasing rainfall is a measure of the relative soil susceptibility to erosion. Susceptibility to erosion increases according to the following order of changes in the elevation points: moderate decrease followed by substantial increase < substantial decrease followed by small decrease < moderate decrease followed by moderate decrease (table 9.2).

Table 9.2 Surface elevation point patterns and variations in runoff and soil loss (ranges of values)

Patterns of change in soil surface elevation points	**Rain 2**			**Rain 3**		
	a-b	**Q**	**E**	**b-c**	**Q**	**E**
moderate decrease followed by moderate decrease	1 - 5	6 - 34	28 - 229	1 - 4	32 - 68	179 - 614
substantial decrease followed by small decrease	2 - 13	8 - 49	38 - 92	1 - 2	23 - 65	34 - 220
moderate decrease followed by substantial increase	-1 - 1	0	0	-10 - -1	0 - 7	0 - 33

a-b = elevation difference in mm between ploughing and rain 2; b-c = elevation difference in mm between rain 2 and rain 3; Q = runoff (mm), E = soil loss (g/m^2).

The first pattern exhibits a linear trend in the variation of the soil surface elevation points, suggesting that erosion increases with increasing rainfall. The second and the third patterns show significant curvature in the variation of the soil surface elevation points, indicating a decrease in soil erosion (figure 9.1). Linear and nonlinear relationships between the changes in the soil surface elevation points and rainfall can be attributed to differences in soil properties.

Behaviour differences are controlled by differences in soil properties, in particular those properties that control permeability and regulate infiltration and percolation. On Vertisols, for instance, cracks absorb the rain water and it is only after closing of the cracks that runoff starts. The horizon sequence in Lixisols and Planosols includes coarse-textured topsoil layers (Ap and A2) above heavy, hard and structureless subsoil layers (Btd and Bt). These contrasting layers promote saturation overland flow (de Ploey and Imeson, 1986; Kuipers, 1986), which contributes to the deterioration of the surface structure and the structural stability.

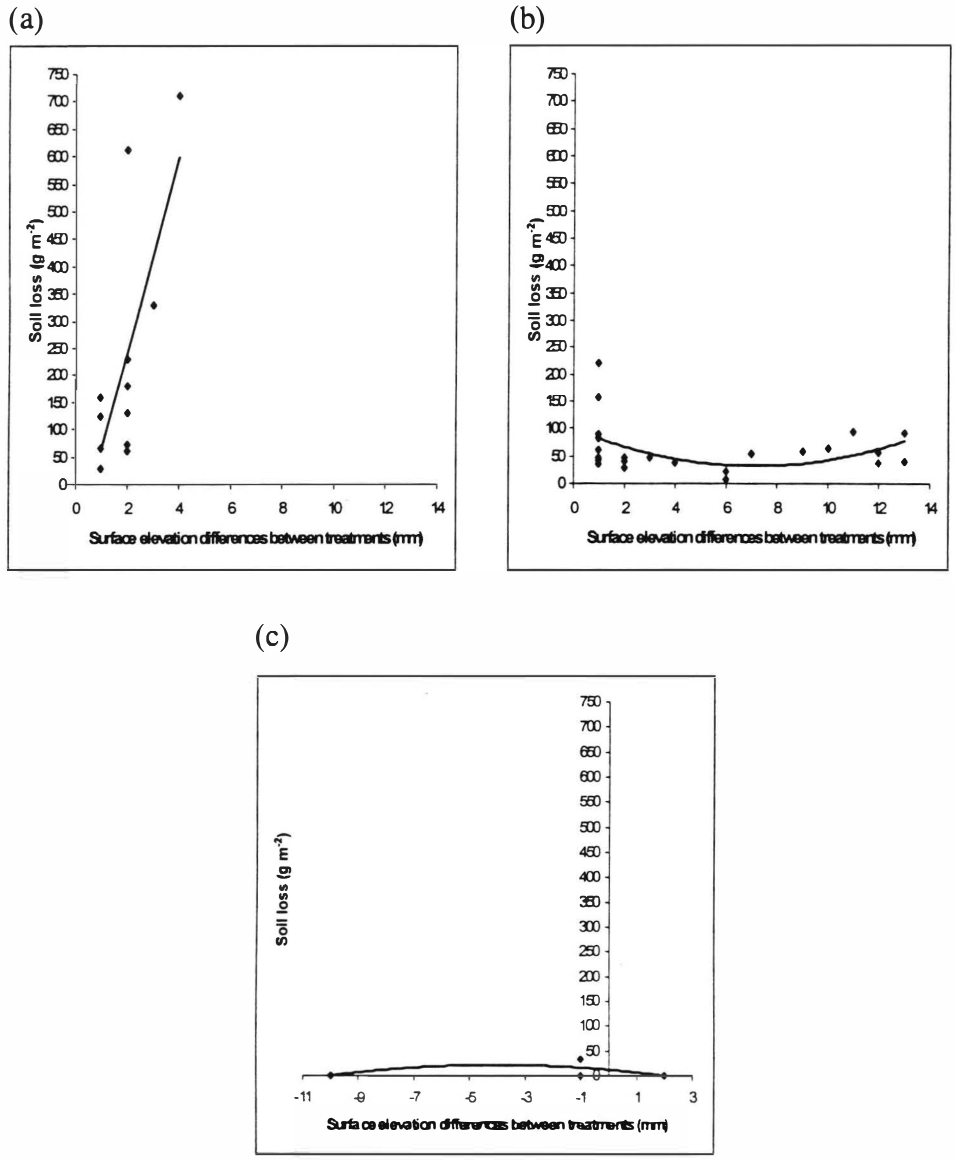


Figure 9.1 Relationships between pattern of change in soil surface elevation points and soil loss: (a) moderate decrease followed by moderate decrease; (b) substantial decrease followed by small decrease; and (c) moderate decrease followed by substantial increase.

The differential behavior of the erosion classes can be attributed to the modifications that affect the topsoil characteristics, such as clay and organic matter contents, and the thickness of the topsoil layers according to erosion degrees (Lal, 1988). More eroded soils (Lixisols and Planosols) have a higher clay content (>20 %) in the surface horizons than less eroded ones. A higher clay content promotes a stronger cohesion of the soil surface aggregates, which resist to slaking. Resistant clods maintain the depression storage, enhance infiltration and retard erosion. But as the rain proceeds, saturation overland flow occurs and the apparent resistance of eroded soils to runoff and erosion decreases consistently. On moderately and severely eroded Vertisols, cracks are less efficient in absorbing water. Less eroded soils present thicker topsoil layers (>15 cm) and a higher organic matter content (0.5-1%) than more eroded ones, providing larger water storage capacity.

The variation of the elevation points between consecutive rains can be considered as an important parameter for monitoring the soil erosion process (Mwendera and Feyen, 1992). The rate of decrease of the elevation points may influence the distribution of the erosion features on the relief. Small rates cause pronounced erosion features only downslope, whereas high rates generate erosion features distributed all over the relief.

9.1.2 Spatial dependence of the soil surface elevation points

Variogram parameters were determined for ten selected soil types divided into three patterns of change, representing eroding (moderate decrease followed by moderate decrease), moderately resisting (substantial decrease followed by small decrease) and very resisting (moderate decrease followed by substantial increase) soil surface aggregates, respectively (table 9.3).

Table 9.3 Variogram parameters of the soil surface elevation points for selected soils.

Soil types	Erosion classes	Treat-ment	Variogram model	Slope	Nugget (mm^2)	Sill (mm^2)	Range (cm)	Patterns of change
Lixisols	Severely eroded	a	Spherical	-	138	22	32.8	Moderate decrease followed by moderate decrease
		b	Spherical	-	50	18	31.2	
		c	Spherical	-	96	24	28.8	
Vertisols	Moderately eroded	a	Spherical	-	99	26	17.2	
		b	Spherical	-	35	43	32	
		c	Spherical	-	15	16	23.6	
Vertisols	Severely eroded	a	Linear	1.28	115	-	-	
		b	Linear	0.924	134	-	-	
		c	Linear	1.104	58	-	-	
Cambisols	Moderately eroded	a	Linear	1.71	135	-	-	
		b	Linear	1.457	43	-	-	
		c	Linear	0.868	29	-	-	
Lixisols	Slightly eroded	a	Linear	0.725	34	-	-	Substantial decrease followed by small decrease
		b	Linear	0.814	11	-	-	
		c	Linear	0.92	4	-	-	
Lixisols	Moderately eroded	a	Spherical	-	43	28	40	
		b	Linear	0.624	4	-	-	
		c	Linear	0.72	11	-	-	
Cambisols	Severely eroded	a	Linear	1.204	42	-	-	
		b	Linear	1.488	6	-	-	
		c	Linear	1.015	4	-	-	
Fluvisols	Slightly eroded	a	Linear	1.22	55	-	-	
		b	Linear	0.9	10	-	-	
		c	Linear	0.76	2	-	-	
Planosols	Slightly eroded	a	Linear	1.961	41	-	-	
		b	Linear	0.7	22	-	-	
		c	Linear	0.612	4	-	-	
Vertisols	Slightly eroded	a	Linear	0.9	258	-	-	Small decrease followed by substantial increase
		b	Linear	0.65	218	-	-	
		c	Linear	0.75	369	-	-	

a = surface elevation after ploughing; b = surface elevation after rain 2; c = surface elevation after rain 3.

The variation of the nugget values reflects the differential behaviour of the soil surface elevation points with increasing rainfall. Nugget values increase on severely eroded Lixisols, indicating high variation of the elevation points within short distance due to erosion (figure 9.2). Nugget values also increase on slightly eroded Vertisols, reflecting substantial variations due to swelling clods (figure 9.3). On slightly eroded Lixisols, a decrease of the nugget values with time denotes that soil surface microtopography becomes more uniform (figure 9.4). Similar behaviour is found on moderately eroded Lixisols (figure 9.5), moderately eroded Vertisols (figure 9.6) and severely eroded Vertisols (figure 9.7).

(a) (b)

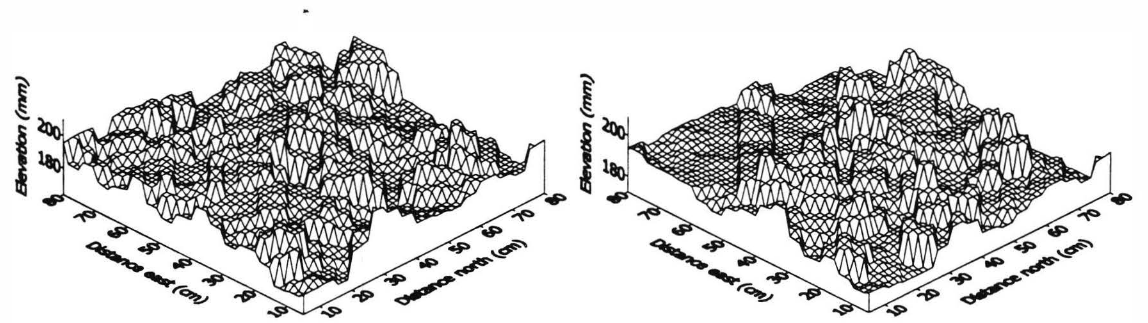


Figure 9.2 Soil surface profile on severely eroded Lixisols after ploughing (a) and after rain 3 (b).

(a) (b)

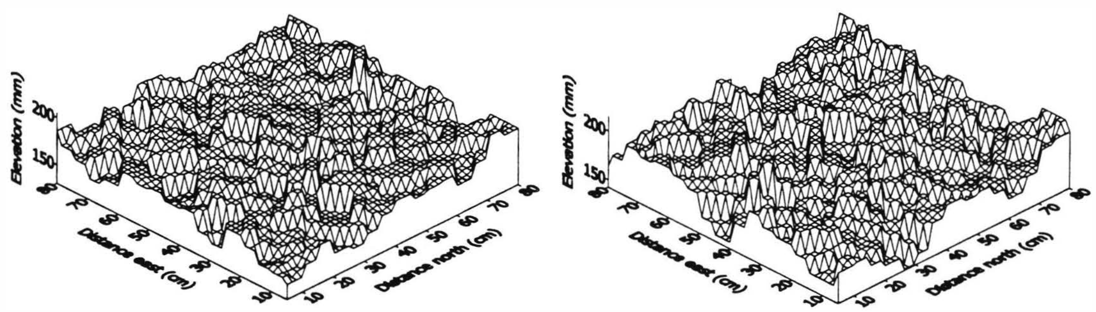


Figure 9.3 Soil surface profile on slightly eroded Vertisols after ploughing (a) and after rain 3 (b).

(a) (b)

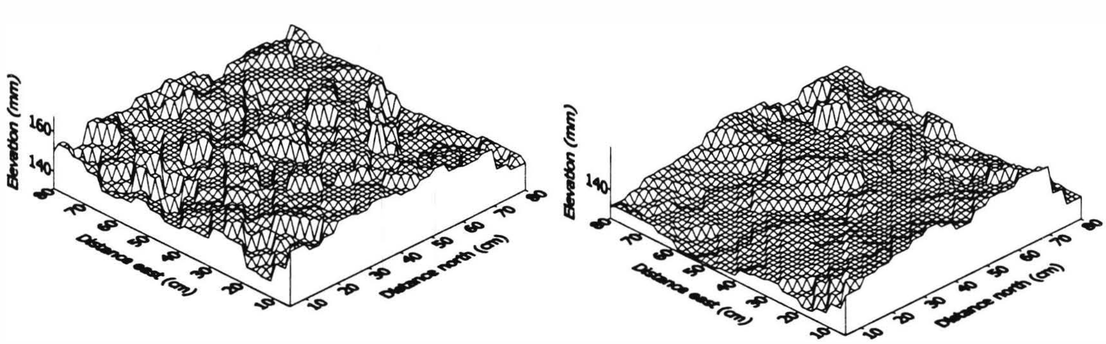


Figure 9.4 Soil surface profile on slightly eroded Lixisols after ploughing (a) and after rain 3 (b).

(a) (b)

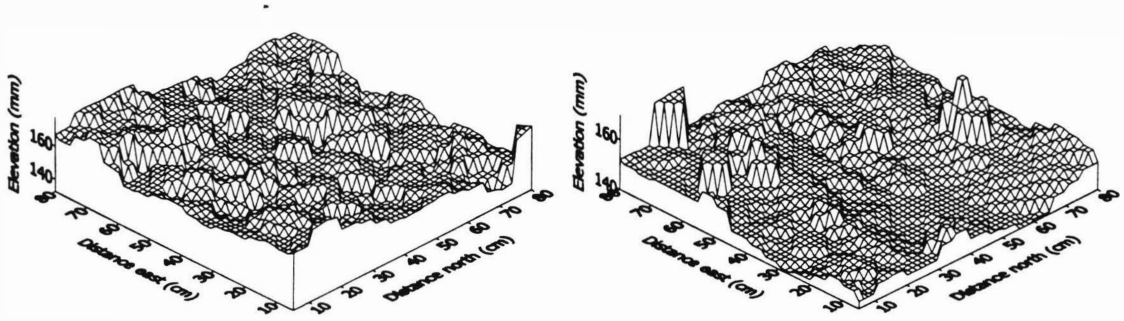


Figure 9.5 Soil surface profile on moderately eroded Lixisols after ploughing (a) and after rain 3 (b).

(a) (b)

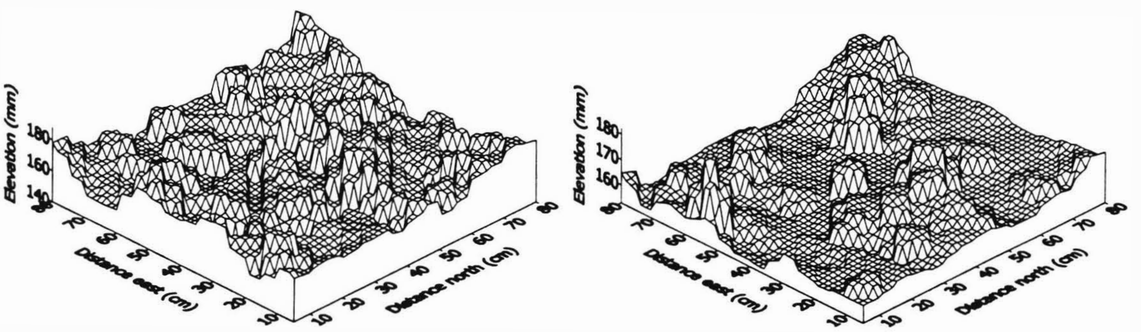


Figure 9.6 Soil surface profile on moderately eroded Vertisols after ploughing (a) and after rain 3 (b).

(a) (b)

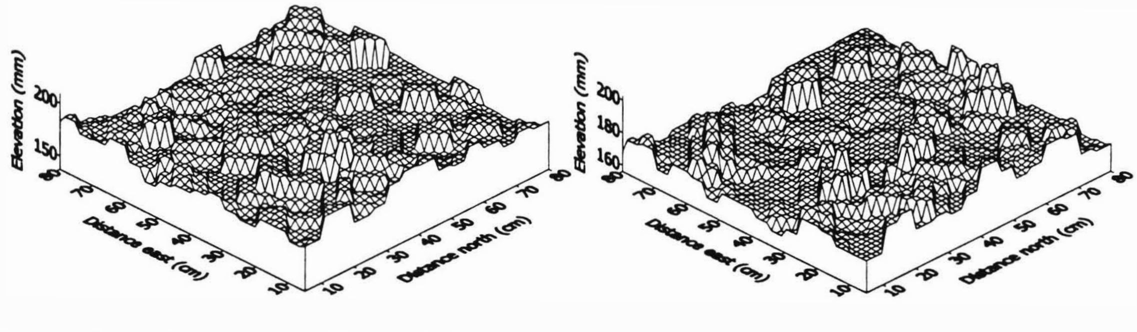


Figure 9.7 Soil surface profile on severely eroded Vertisols after ploughing (a) and after rain 3 (b).

9.2 VARIATIONS OF THE SOIL EROSION INDICATORS AT PLOT SCALE

9.2.1 General behaviour of the erosion indicators in the field

Two plots of 40 x 104 m each were delineated to study the spatial distribution of erosion features, one on moderately eroded Lixisols and another one on moderately eroded Vertisols. Erosion indicators were recorded on a grid at 8 m interval. Field observation revealed relationships among soil erosion indicators.

(1) On moderately eroded Lixisols

On moderately eroded Lixisols where ridge-furrow systems were constructed, there was a positive linearity between the size of the ridge-furrow systems and erosion features. For instance, the resistant clods corresponded to the areas where the ridges were not destroyed by erosion. These areas showed also resistant crust layers on the soil surface. The width of the ridges was almost similar to the original size at the time of construction. Where erosion occurred, the ridge width decreased while the furrow width increased and the furrow depth decreased, accompanied by erosion features such as rills, colluvium and depressions. The changes affecting the size of the ridge-furrow systems under erosion integrate resistant and eroding features.

(2) On moderately eroded Vertisols

On moderately eroded Vertisols without soil surface management, the areas with cracks corresponded to resistant parts. The size of the cracks was considered to be a good indicator of the state of erosion. The wider and deeper the cracks, the less eroded is the soil. The width of the cracks also correlated positively with the soil depth. The cracks absorb runoff water and this reduces erosion. The areas showing no cracks generate high runoff, enhancing erosion. In addition, there was a positive correlation between the size of the cracks and the performance of dry sorghum. In fact, in the semiarid area of Cameroon, a farmer cannot undertake dry sorghum cultivation on Vertisols, if the soils do not show large cracks during the previous dry season.

9.2.2 Descriptive statistics of the erosion indicators

(1) On moderately eroded Lixisols

Table 9.4 gives descriptive statistics of the studied erosion features. Data indicate that many features vary considerably. The pH and sand content have small coefficients of variation (4 and 9%, respectively). Clay and organic matter contents exhibit high coefficients of variation (43 and 38%, respectively). Variables that are strongly influenced by soil management, including the thickness of the topsoil layer, ridge width and furrow depth, have intermediate coefficients of variation ranging from 25 to 33%. The cotton plant height shows a value of 21% for the coefficient of variation.

Table 9.4 Descriptive statistics of the topsoil properties on moderately eroded Lixisols

Erosion indicators	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
Clay content (%)	3	29	7	3	43
Sand content (%)	50	73	62	5.6	9
Organic matter content (%)	0.3	2	0.8	0.3	38
pH (H_2O)	6.2	8.3	7.1	0.3	4
Thickness of topsoil (cm)	6	15	10	2.5	25
Ridge width (cm)	18	69	45	14.5	32
Furrow depth (cm)	3	14	8	2.6	33
Cotton plant height (cm)	43	139	97	20.7	21

(2) On moderately eroded Vertisols

Like on moderately eroded Lixisols, the pH and sand content display small coefficients of variation on moderately eroded Vertisols (4 and 13%, respectively). The sorghum plant height and the cracked area percentage exhibit high coefficients of variation (41 and 165%, respectively). Clay and organic matter contents display intermediate values of the coefficient of variation.

Table 9.5 Descriptive statistics of the topsoil properties on moderately eroded Vertisols

Erosion indicators	Minimum	Maximum	Mean	Standard deviation	Coefficient of variation (%)
Clay content (%)	12	37	26	5.1	20
Sand content (%)	29	51	37	4.9	13
Organic matter content (%)	0.6	1.8	1.1	0.2	18
pH (H_2O)	7.4	8.6	8.1	0.3	4
Cracked area (%)	0	13	2	3.3	165
Sorghum plant height (cm)	0	208	126	51.4	41

9.2.3 Relationship between erosion indicators and slope length

Obviously, the variations of the erosion indicators tend to be more substantial along the slope than along the contour. Regression analysis was carried out to examine the functional relationship between erosion features and slope length.

(1) On moderately eroded Lixisols

The values of many variables decrease as a function of the distance downslope on moderately eroded Lixisols (table 9.6). For instance, the slope values for clay content, organic matter content and pH are -0.05, -0.008 and -0.005, respectively. Only the sand content increases with increasing slope length (0.14).

Table 9.6 Regression of the topsoil properties with the slope length on moderately eroded Lixisols

Erosion indicators	Intercept	Slope	R^2	P-value
Clay content (%)	9	-0.05	0.2318	6.12E-06
Sand content (%)	54.4	0.14	0.5915	7.9E-17
Organic matter content (%)	1.2	-0.008	0.4937	3.73E-13
pH (H_2O)	7.3	-0.005	0.2981	1.6E-07
Thickness of topsoil (cm)	12.6	-0.05	0.3675	2.54E-09
Ridge width (cm)	65.2	-0.393	0.6399	5.56E-19
Furrow depth (cm)	11.2	-0.055	0.3908	5.67E-10
Cotton plant height (cm)	124	-0.525	0.5626	1.16E-15

(2) On moderately eroded Vertisols

Similarly, the values of many erosion indicators decrease with increasing slope length downslope, on eroded Vertisols. For instance, the slope values for clay and organic matter contents are –0.052 and –0.002, respectively. The cracked area and sorghum plant height are also negatively correlated with the slope length. In contrast, sand content and pH increase with increasing slope length (0.051 and 0.003, respectively).

Table 9.7 Regression of the properties of the topsoil layer with the slope length on moderately eroded Vertisols

Erosion indicators	Intercept	Slope	R^2	P-value
Clay content (%)	29.1	-0.052	0.0909	0.0066
Sand content (%)	34.3	0.051	0.0926	0.006
Organic matter content (%)	1.2	-0.002	0.1081	0.0029
pH (H_2O)	7.9	0.003	0.1074	0.003
Cracked area (%)	3.12	-0.022	0.0394	0.0772
Sorghum plant height (cm)	174.4	-0.94	0.2918	2.32E-07

Many variables decrease as a function of the distance downslope on both moderately eroded Lixisols and moderately eroded Vertisols. The statistical relationships between erosion indicators and slope length allow to make predictions on erosion severity. These relationships seem to be more consistent on moderately eroded Lixisols than on moderately eroded Vertisols. The P-values on moderately eroded Lixisols (6.12E-06 to 5.56E-19) are lower than on moderately eroded Vertisols (0.0029 to 2.32E-07).

Less consistency in the variation of the erosion indicators with respect to the location on the slope, on moderately eroded Vertisols, suggests that erosive processes can take place anywhere in the field, independently on the slope length. In other words, cumulative erosion effect causes pronounced damage only dowslope on moderately eroded Lixisols, whereas on moderately eroded Vertisols erosion indicators can occur at short distance all over the slope. The linear relationship between erosion indicators and slope length provides a convenient framework for modelling and predicting erosion indicators along the slope. As there is a strong interaction between soil and slope length, different slope adjustment factors are needed for different soils. Meyer and Harmon (1989), Ben-Hur et al. (1992), Kinnell and Cummings (1993) report similar results.

9.2.4 Spatial dependence of the erosion indicators

The spatial dependence of the topsoil properties, soil management characteristics and crop performance as modified by soil erosion was assessed using variogram parameters. Two main sources of variation were examined: (1) differences between observation points within a plot and (2) soil-to-soil differences between plots. The separation of the point variations from the soil variations was achieved by studying the experimental variogram.

(1) Spatial variations within soil types

(a) On moderately eroded Lixisols

On moderately eroded Lixisols, erosion indicators show mainly transitive (spherical and exponential) variogram structures (table 9.8). The clay content displays a linear variogram structure, indicating continuous variation with slope length. Graphical representations of the variograms for each selected erosion indicator are shown in figures 9.8 and 9.9.

Table 9.8 Variogram parameters for topsoil properties on moderately eroded Lixisols

Erosion indicators	Variogram model	Nugget value	Slope	Sill	Range (m)
Clay content (%)	Linear	1.89	0.099	-	-
Sand content (%)	Spherical	6.5	-	7.15	22.05
Organic matter content (%)	Exponential	0.0138	-	0.042	38.22
pH(H_2O)	Exponential	0.0203	-	0.042	31.36
Thickness of topsoil (cm)	Spherical	1.064	-	3.344	9.8
Ridge width (cm)	Spherical	15.12	-	63	25.95
Furrow depth (cm)	Spherical	1.89	-	2.982	29.4
Cotton plant height (cm)	Spherical	30.6	-	156.6	15.68

Some variables have similar range values. For instance, organic matter content and pH show range values of 38.22 and 31.36 m, respectively. The similarity in range can be explained by a strong dependence of pH on organic matter. Likewise, the ridge width and furrow depth display similar range values of 25.95 and 29.4 m, respectively. The similarity and dissimilarity observed in the variogram structures of the variables can be explained by interactions that exist among soil properties and by selective erosion.

The topsoil layer is moved during the construction of the ridge-furrow systems. This results in cut and fill areas showing differences in A horizon thickness, organic matter content, clay content, sand content and pH. Selective erosion controls the spatial distribution of particle size, causing a decrease of clay content and an increase of sand content with increasing slope length. Decreasing clay content is accompanied with organic matter depletion, which results in pH decrease.

A poor clay-organic matter complex decreases the resistance of soil to erosion. As a consequence, the thickness of the topsoil decreases. On the less eroded areas in the upper part of the plot, the topsoil mainly consists of an A horizon, whereas on the more eroded areas downslope the topsoil consists partly of A horizon and partly of B horizon.

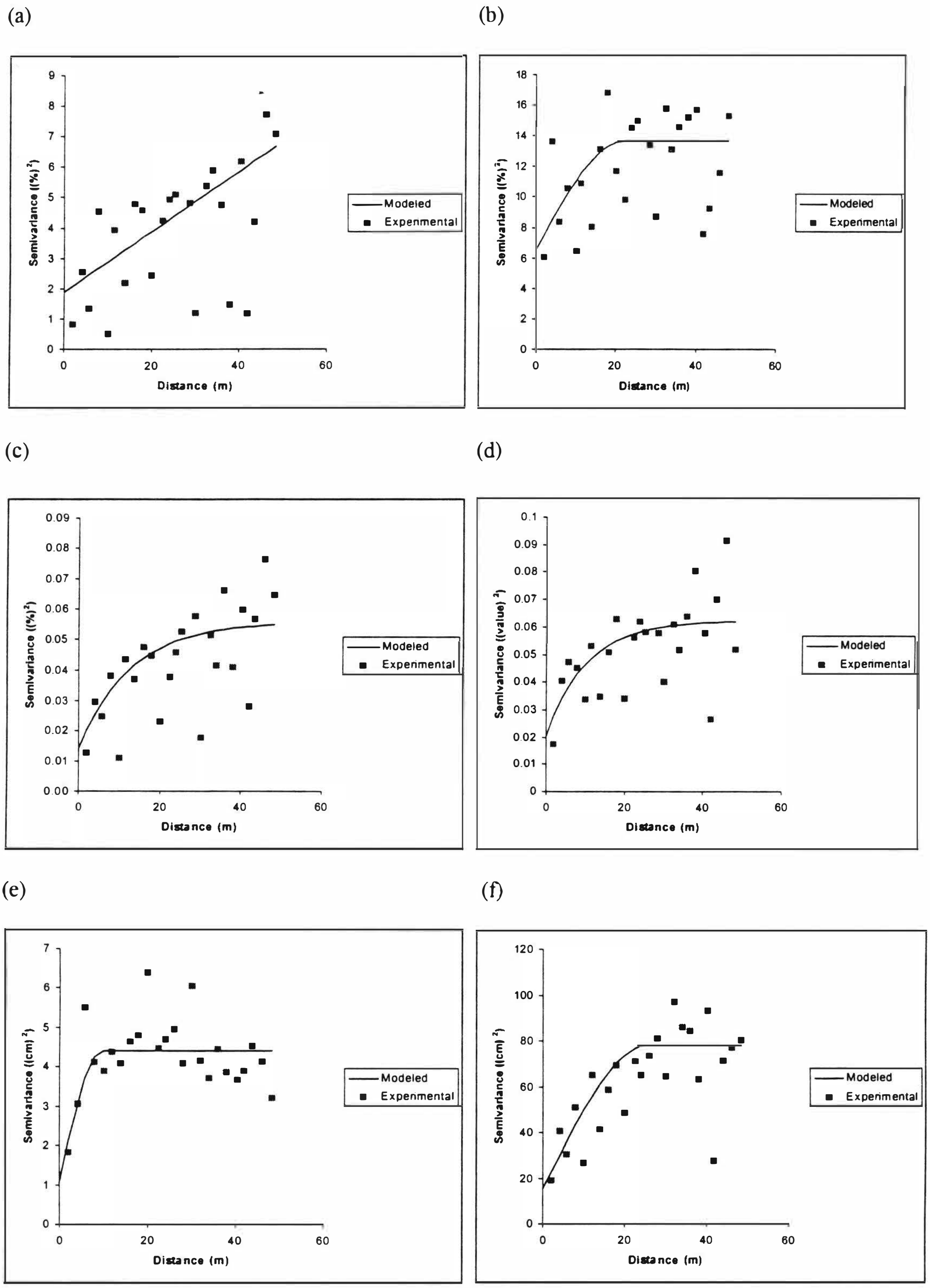


Figure 9.8 Variograms for the properties of the topsoil layer on moderately eroded Lixisols: (a) clay content, (b) sand content, (c) organic matter content, (d) pH, (e) thickness of the topsoil layer, and (f) ridge width.

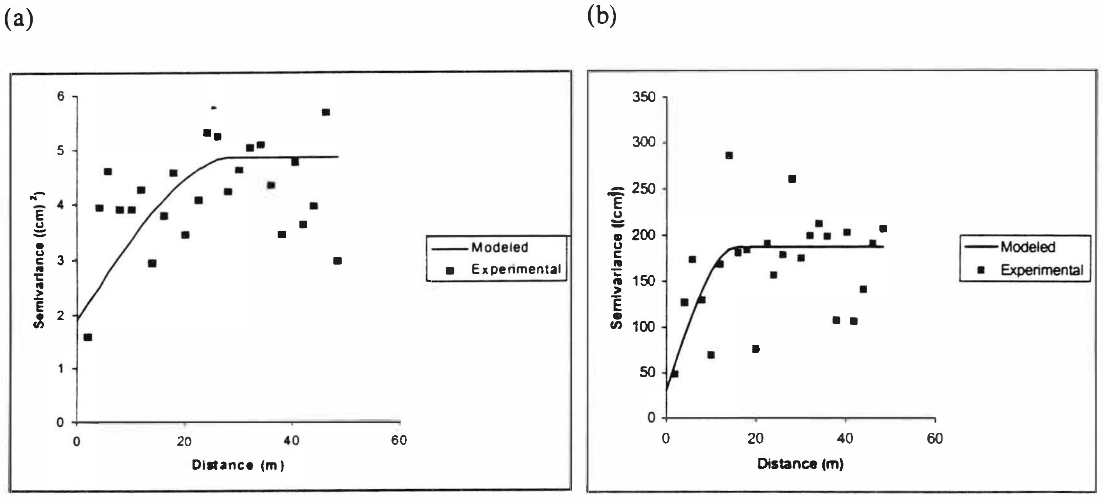


Figure 9.9 Variograms for the properties of the topsoil layer on moderately eroded Lixisols: (a) furrow depth, and (b) cotton plant height.

A high range of spatial dependence for the ridge-furrow system and a small range of spatial dependence for the thickness of the topsoil layer confirm the above hypothesis. A longer range and a smaller sill for the ridge-furrow system are related to continuous and homogenous agricultural practices, which cause smoother and less frequent fluctuations. Spatial variations of the size of the ridge-furrow system can then be used to quantify and map erosion on cultivated lands. Dobermann (1994) and Ricardo (1994) report similar results.

The cotton plant height and the A horizon exhibit similar ranges of spatial dependence, indicating that the development of the cotton plant is related to the variation of the A horizon thickness. In fact, the A horizon is the main source of the plant nutrients. The crop performance can be seen as a target that has also a spatial dimension. This suggests that the identification and mapping of erosion indicators should be integrated with the field variations of the soil properties causing yield differences.

(2) On moderately eroded Vertisols

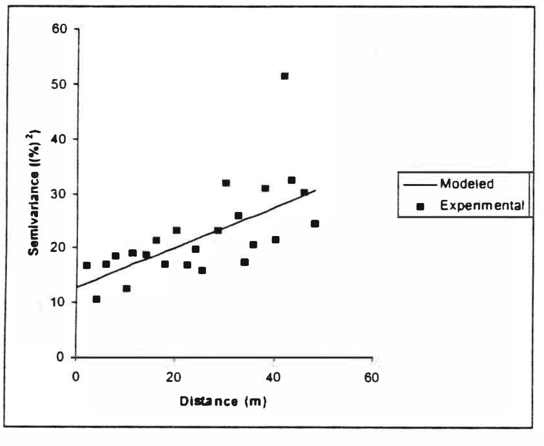
On moderately eroded Vertisols, many variables exhibit a linear variogram structure. The Sorghum plant height shows higher spatial dependence than pH. The slope values are 39.53 and 0.00288, respectively. Clay and sand contents exhibit intermediate spatial dependence.

Organic matter content displays an exponential variogram model, whereas cracked area percentage shows a spherical variogram model. The nugget values are 0.0036 and 5.5, the sill values are 0.032 and 11 and the range values are 29.4 and 45.57, respectively (table 9.9). The variogram for each selected erosion feature on moderately eroded Vertisols is represented in figures 9.10 and 9.11.

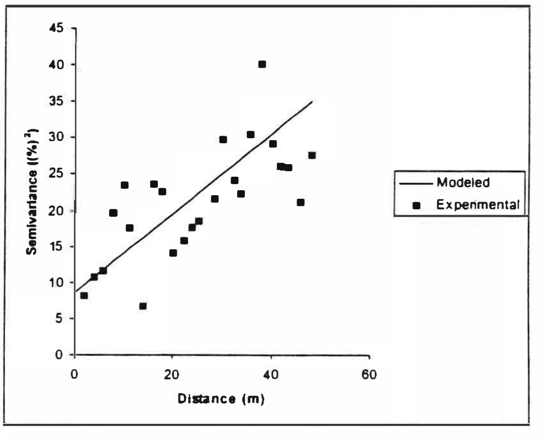
Table 9.9 Variogram parameters for topsoil properties on moderately eroded Vertisols

Erosion indicators	**Variogram model**	**Nugget value**	**Slope**	**Sill**	**Range (m)**
Clay content (%)	Linear	12.72	0.37	-	-
Sand content (%)	Linear	8.51	0.55	-	-
Organic matter content (%)	Exponential	0.0036	-	0.032	29.4
pH(H_2O)	Linear	0.0128	0.00288	-	-
Cracked area (%)	Spherical	5.5	-	11	45.57
Sorghum plant height (cm)	Linear	464	39.53	-	-

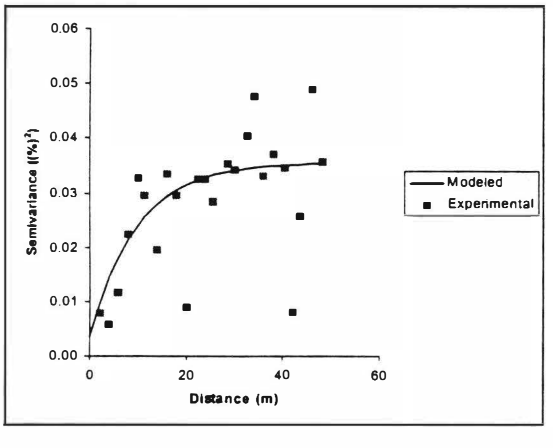
(a)



(b)



(c)



(d)

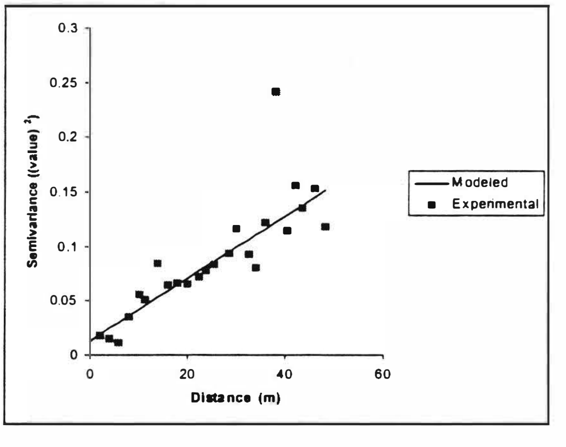


Figure 9.10 Variograms for topsoil properties on moderately eroded Vertisols: (a) clay content, (b) sand content, (c) organic matter content, and (d) pH.

(a) (b)

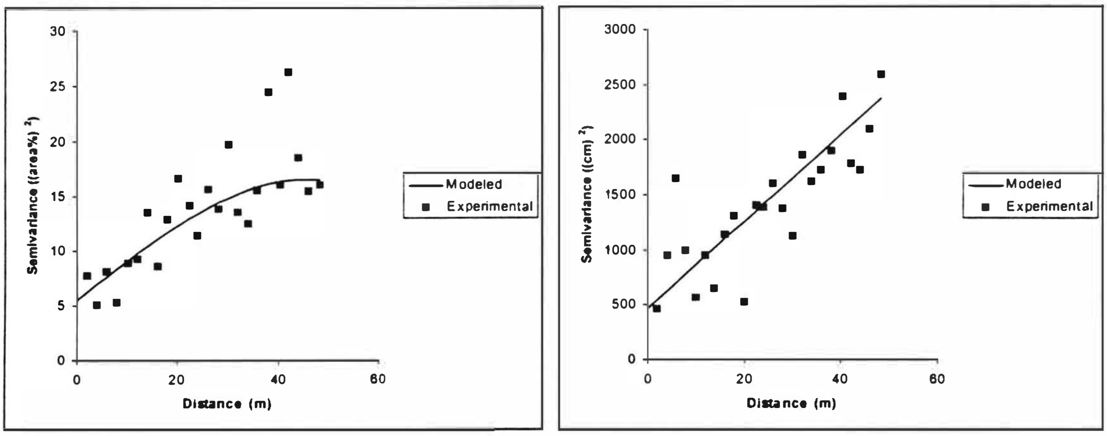


Figure 9.11 *Variograms for topsoil properties on moderately eroded Vertisols:* (a) cracked area, and (b) sorghum plant height.

(2) Spatial variations between soil types

Erosion indicators mainly show transitive (spherical or exponential) variogram structures on moderately eroded Lixisols and linear variogram structure on moderately eroded Vertisols. Similar variograms for the same type of erosion feature indicate common origins, whereas significantly different variograms denote distinct erosion processes responsible for the pattern of the variogram structures. The interpretation of the variogram structures can be based on the relationships between variables and erosion.

Differences in variogram structure for sand content are attributed to differences in initial sand content. Sand content is high in the topsoil layer of moderately eroded Lixisols and low in that of moderately eroded Vertisols. Differences in variogram structure for pH denote significantly distinct sources of variation. The variation of pH on moderately eroded Lixisols is due to the variation of organic matter content, while the variation of pH on moderately eroded Vertisols is related to the depth of the parent material. Transitive variogram structures for the variables on moderately eroded Lixisols can be related to the crusting process, which causes apparently high resistance of the topsoil to erosion in the upper part of the plot. On resistant soil surfaces, soil properties are less variable. In contrast, the linear variogram model for the variables on moderately eroded Vertisols translates a high variability of the soil properties at short distance and suggests a strong susceptibility of the topsoil layers to erosion.

Clay content has a linear variogram structure on moderately eroded Lixisols as well as on moderately eroded Vertisols. Whatever the type of soil might be, clay particles are easily transported by runoff after they are detached from soil surface aggregates by raindrop impact or by surface flow. A linear variogram model for clay content illustrates a continuous spatial dependence along the slope, which confirms the susceptibility of clay particles to transport.

9.2.5 Prediction of erosion indicators over the investigation area

Experimental plots were stratified into classes of gradual changes through linear interpolation using the kriging technique. Their boundaries were mapped to highlight variations in composition from place to place within the area of interest (figures 9.12 to 9.15).

(1) On moderately eroded Lixisols

The predicted values vary between 6.5 and 13 cm, 55 and 130 cm, and 22 and 62 cm for the thickness of the topsoil layer, height of the cotton plant and ridge width, respectively. High values (presented in red colour) of erosion indicators occur all over the summit area of the experimental plot. Low values (presented in blue colour) of erosion indicators occur predominantly downslope of the experimental plot, whereas intermediate values (light red colour) of erosion indicators appear in the middle part of the slope (figures 9.12 and 9.13).

The differences that occur in the predicted values according to the position on the slope suggest that the degrees of erosion severity differ from place to place, along the slope. The values of the soil properties, management practices and crop characteristics are negatively correlated with erosion. This is illustrated by a decrease of the thickness of the topsoil layer, ridge width, furrow depth and height of the cotton plant along the slope, from the summit downslope. The shallow depth of the topsoil layer (<10 cm) downslope signals conditions of severely eroded Lixisols and the absence of deposition of soil materials in that zone. This indicates that deposition processes depend on the slope length, slope gradient, soil properties and rainfall characteristics. In general, soil erosion factors influence also deposition of soil materials.

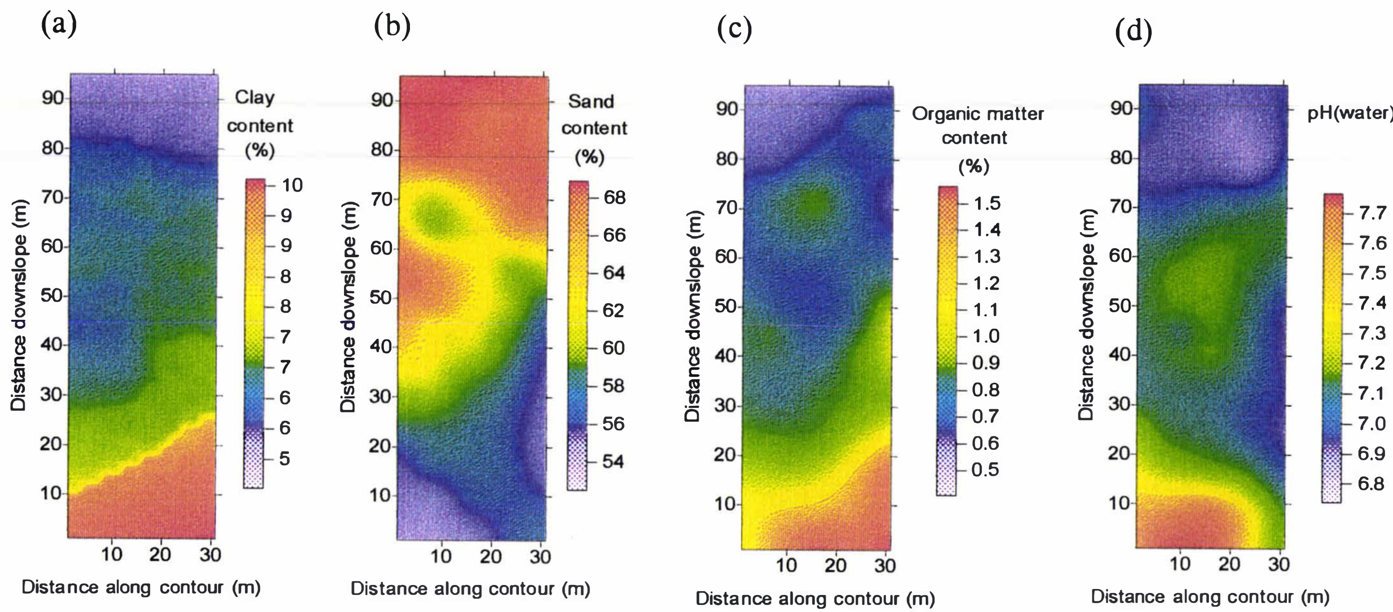


Figure 9.12 Spatial distribution of topsoil properties on moderately eroded Lixisols: (a) clay content, (b) sand content, (c) organic matter content, and (d) pH (H_2O).

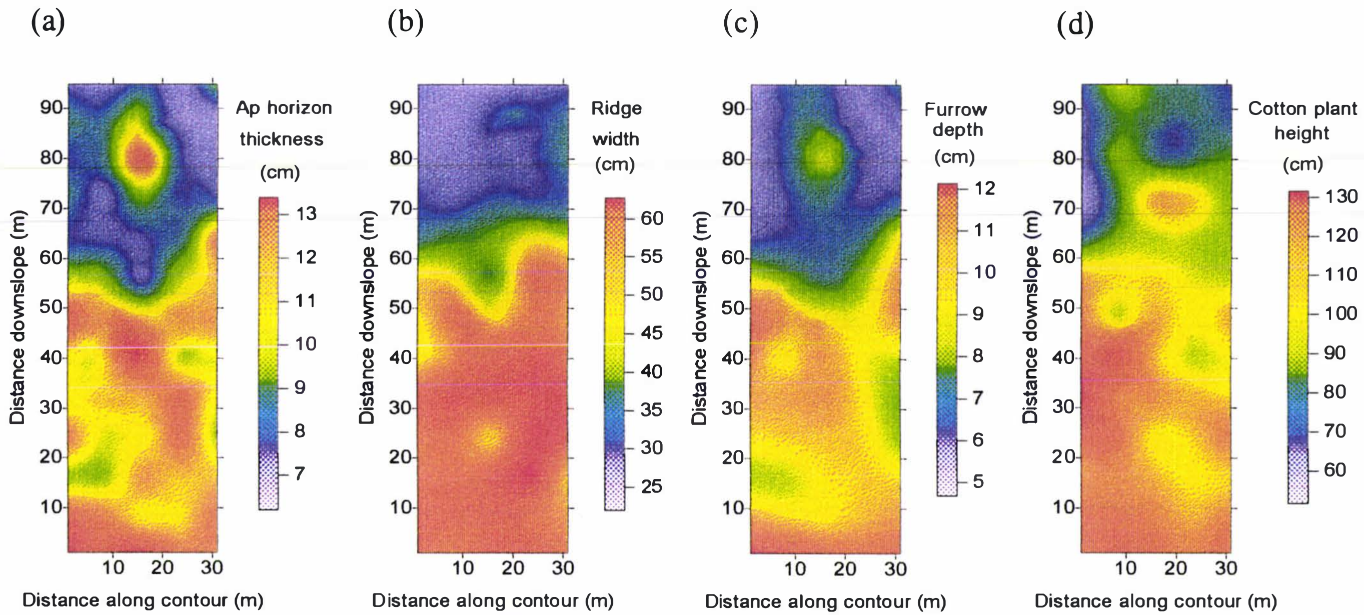


Figure 9.13 Spatial distribution of topsoil properties on moderately eroded Lixisols: (a) thickness of the topsoil layer, (b) ridge width, (c) furrow depth, and (d) cotton plant height.

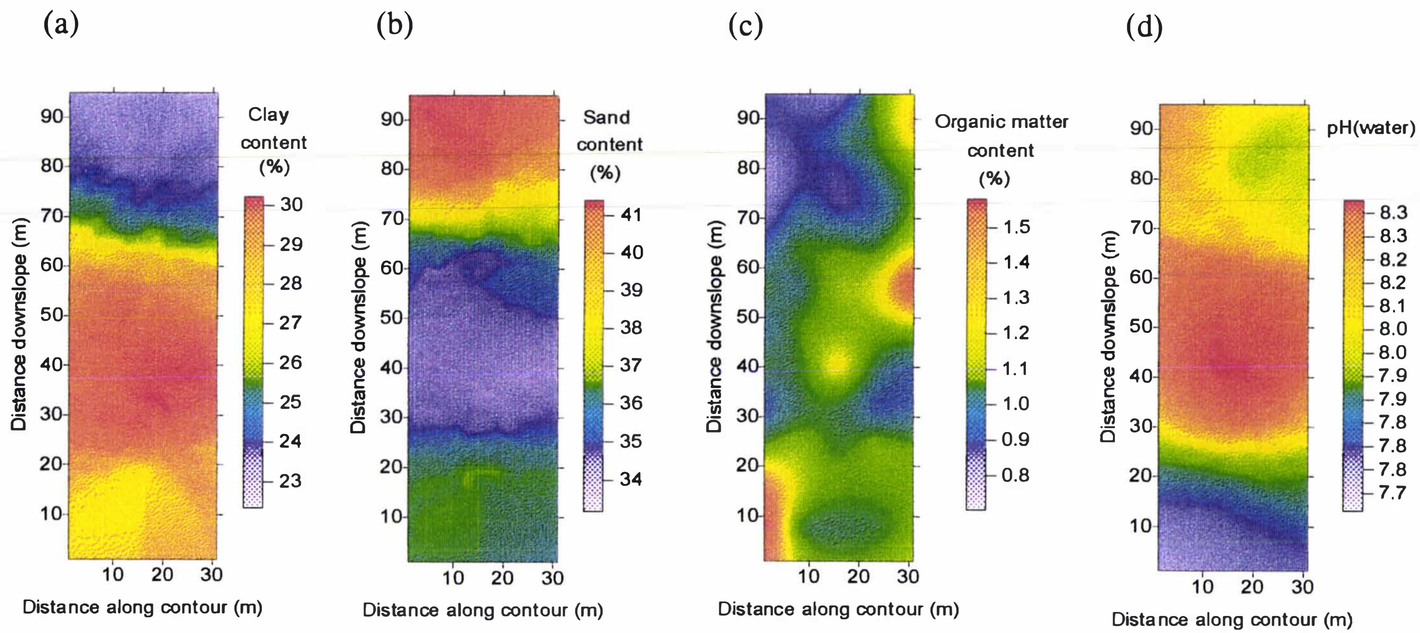


Figure 9.14 Spatial distribution of topsoil properties on moderately eroded Vertisols: (a) clay content, (b) sand content, (c) organic matter content, and (d) pH (H_2O).

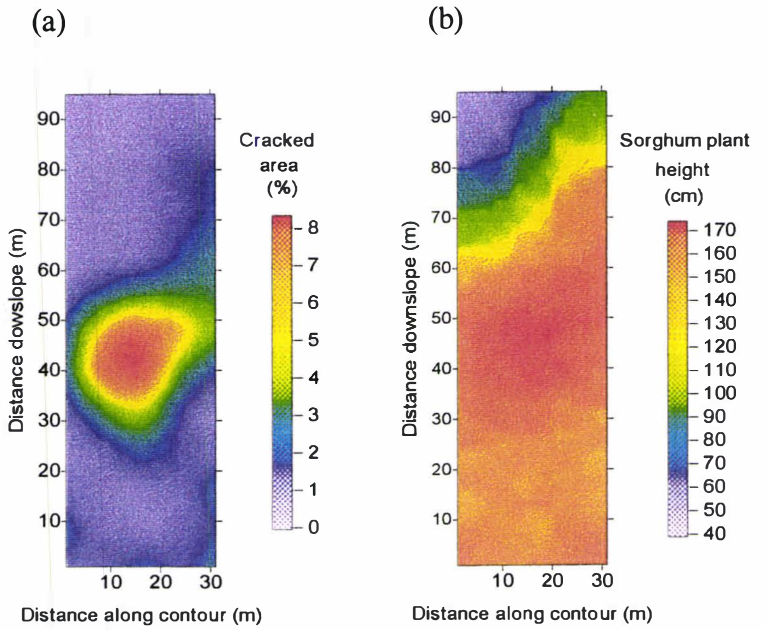


Figure 9.15 Spatial distribution of topsoil properties on moderately eroded Vertisols: (a) cracked area, and (b) sorghum plant height.

(2) On moderately eroded Vertisols

On Vertisols, the predicted values range from 0.5 to 8% and from 40 to 170 cm for the cracked areas and sorghum plant height, respectively. The highest values (red colour) occupy mostly the middle part of the area, while the smallest values (blue colour) are dominantly found downslope (figures 9.14 and 9.15). However, the presence of small to moderate values for cracked area (2 to 5%) and sorghum plant height (130 to 150 cm) on the summit of the plot indicates moderate to severe erosion conditions. This suggests that, on moderately eroded Vertisols, substantial erosion can occur in the upper part of a field. The slope length and pH display a positive linearity, indicating that pH values can be predicted from the slope length. An increase of pH with increasing slope length is attributed to variations of the depth to the C horizon. As erosion increases with increasing slope length, the depth to the parent material decreases, affecting the pH values of the topsoil layer. The C horizon of the Vertisols developed on embrechite shows higher pH values than the C horizon of the Lixisols developed on granite or gneiss.

On each soil type, the predicted and observed values of the variables are similar. This illustrates the ability of the geostatistical procedures to highlight at what scale erosion indicators vary and to detect changes in the spatial variability structure. As an exception, there is a substantial gap between the observed maximum value (29%) and the predicted maximum value (10%), for the clay content on moderately eroded Lixisols, but this does not influence the interpretation of the results because the mean values are similar (table 9.10). Similar comments can be made for the observed and predicted values on moderately eroded Vertisols (table 9.11).

Table 9.10 Observed and predicted values of topsoil properties on moderately eroded Lixisols

Erosion indicators	**Observed**			**Predicted**		
	Minimum	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**
Clay content (%)	3	29	7	5	10	7.5
Sand content (%)	50	73	62	53	69	61
Organic matter content (%)	0.3	2	0.8	0.4	1.7	1
pH(H_2O)	6.2	8.3	7.1	6.7	7.8	7.2
Thickness of topsoil (cm)	6	15	10	6	13.5	10
Ridge width (cm)	18	69	45	22.5	62.5	42.5
Furrow depth (cm)	3	14	8	5	12	8.5
Cotton plant height (cm)	43	139	97	50	130	95

Table 9.11 Observed and predicted values of topsoil properties on moderately eroded Vertisols

Erosion indicators	**Observed**			**Predicted**		
	Minimum	**Maximum**	**Mean**	**Minimum**	**Maximum**	**Mean**
Clay content (%)	12	37	26	22	30	26.5
Sand content (%)	29	51	37	33	42	37.5
Organic matter content (%)	0.6	1.8	1.1	0.7	1.6	1.2
pH(H_2O)	7.4	8.7	8.1	7.7	8.4	8.6
Cracked area (%)	0	13	2	0	8.5	4
Sorghum plant height (cm)	0	208	126	40	175	113

9.2.6 Implications for soil erosion and conservation measures

(1) On moderately eroded Lixisols

On moderately eroded Lixisols, farmers constructed ridge-furrow systems along the slope. A ridge was more than 100 m long. The thickness of the topsoil layer, ridge width, furrow depth and cotton plant height show spatial dependence, with a maximum range of spatial variation of 55 m from the summit downslope. Beyond that range, the thickness of the topsoil layer is less than 10 cm, indicating conditions of severely eroded soils. Conclusively, one may say that beyond approximately 55 m from the summit erosion becomes more damaging, causing poorer conditions for crop development. It is expected that, for a field of 100 m long, about 50% of the total area is exposed to be seriously affected by erosion. The zone of severe damage consists mainly of the lower part of the field. These results point towards the need for drainage control, especially in the middle part of the field. A cut-off drain at approximately 55 m from the divide may prevent run-on from entering the lower part of the field and causing erosion. In other words, diverting excess rainfall and reducing the erosive power of runoff at 55 m interval along the slope entails a much longer slope.

(2) On moderately eroded Vertisols

Moderately eroded Vertisols show areas of actual damage distributed all over the field. Thus soil and water conservation measures must cover large areas. In addition, the concentration of cracks in the middle part of the plot may create conditions for gully initiation, when the absence of cracks in the upper part of the field generates runoff. The crack areas located below the summit act as sink and absorb runoff water. But the absence of cracks in the lower part prevents percolation of excess runoff and causes saturation. Saturated regions contribute to the deterioration of the surface structure and the structural stability and promote erosion. This process may explain the presence of gullies on moderately eroded Vertisols encountered on relatively flat areas.

The construction of microcatchments or "diggets" allows to collect excess rainfall and increase water storage, reducing saturation and erosion of the cracked areas downslope. An increase of water storage enhances soil moisture content, which increases sorghum yields. In some places nearby the study area, farmers construct "diggets" on Vertisols to store rainwater during the rainy season. This technique should be recommended.

9.3 CONCLUSION

Erosion indicators, including the properties of the topsoil, characteristics of the soil management and crop performance, are spatially dependent and modified by erosion. Two main sources of variation were identified (1) from the differences between observation points within a plot and (2) from the soil-to-soil differences between plots. Separating the point variations from the soil variations was achieved by studying the experimental variogram. Most of erosion indicators showed transitive (spherical and exponential) variogram structures on moderately eroded Lixisols, whereas most of erosion indicators on moderately eroded Vertisols exhibited a linear variogram structure. The similarity of the variogram patterns within a plot suggests that the variations within a field arose mainly from the nugget effect due to variable-to-variable differences. The contribution of the soil-to-soil differences were reflected by the differences in the variogram structure of the variables between plots. The spatial distribution of the erosion indicators on a slope provided two clues to determine the constraints to crop development and establish appropriate soil and water conservation measures. The first clue emphasizes the area of actual damage as a percentage of the field size, expressing what coverage of the field is already eroded. This knowledge gives an insight to whether soil conservation is needed to cover the whole field (e.g. on moderately eroded Vertisols) or if a single measure can do as well (e.g. on moderately eroded Lixisols). The second clue focuses on the areas with high erosion severity to know where to place the soil conservation measures.

CHAPTER 10

INTERACTIONS AMONG INTERRILL SOIL EROSION INDICATORS

Twenty five sites, representing the regional soil types with different erosion classes, were subjected to artificial rainfall. Three erosion classes were identified for each soil type, namely (1) slightly eroded, (2) moderately eroded, and (3) severely eroded. A field rainfall simulator was used for studying erosion and hydrological processes at one-square-meter plots. Three rain showers were simulated at different intensities and durations. Plots were bare and ploughed with a hand hoe. The method allowed explicit consideration of factors determining runoff, sediment concentration and soil surface microtopography in detail.

In this chapter, the results from chapters 5, 7, 8 and 9 are integrated to analyze the interactions among the interrill erosion indicators and understand the elemental interrill erosion processes. Such knowledge forms the basis for establishing a local model of interrill soil erosion.

10.1 SPLASH DETACHMENT, RUNOFF AND INTERRILL SOIL LOSS OVER TIME

10.1.1 Relationships within rainfall events

Throughout a rainfall event, interactions between splash detachment and soil loss permit to distinguish four situations, where: (1) splash detachment is higher than soil loss; (2) splash detachment and soil loss are similar; (3) splash detachment is lower than soil loss; and (4) splash detachment-soil loss ratio fluctuates (figures 10.1 to 10.6).

(a) (b)

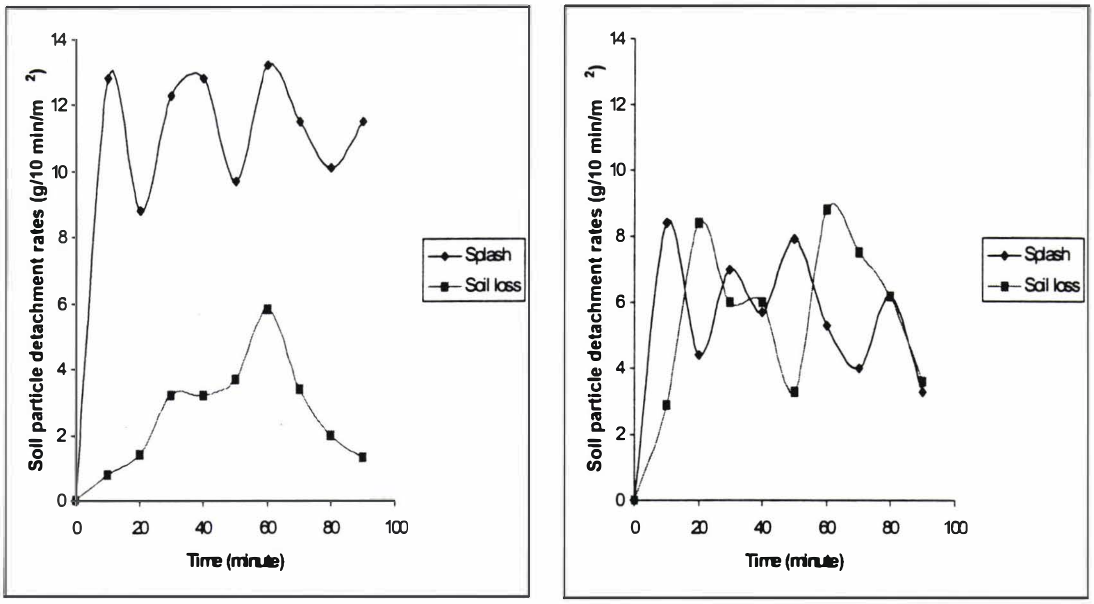


Figure 10.1 Temporal variations of soil particle detachment rates showing splash-soil loss relationships: (a) splash is higher than soil loss on slightly eroded Lixisols in rain 3; and (b) splash and soil loss are similar on moderately eroded Lixisols in rain 2.

(a) (b)

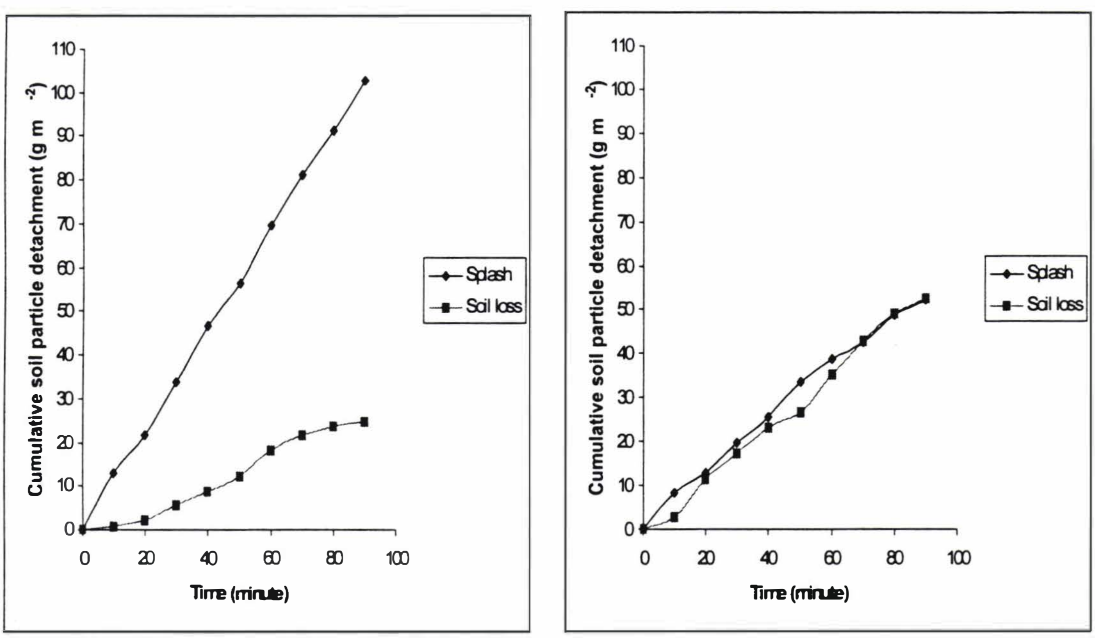


Figure 10.2 Cumulative soil particle detachment showing splash-soil loss relationships: (a) splash is higher than soil loss on slightly eroded Lixisols in rain 3; and (b) splash and soil loss are similar on moderately eroded Lixisols in rain 2.

(a) (b)

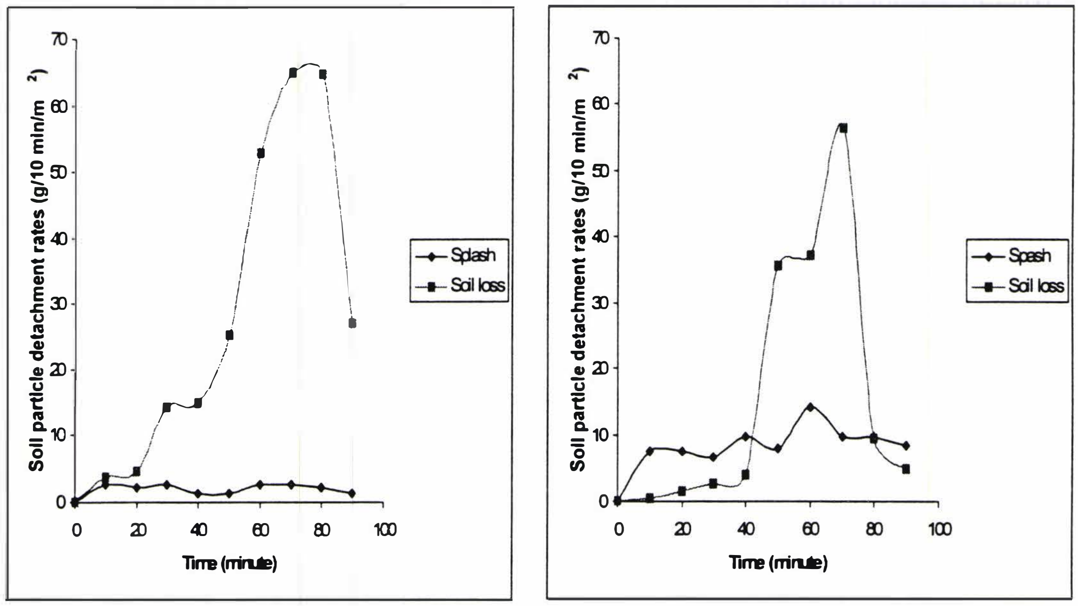


Figure 10.3 Temporal variations of soil particle detachment rates showing splash-soil loss relationships: (a) splash is smaller than soil loss on severely eroded Planosols; and (b) splash-soil loss ratio fluctuates on severely eroded Lixisols in rain 3.

(a) (b)

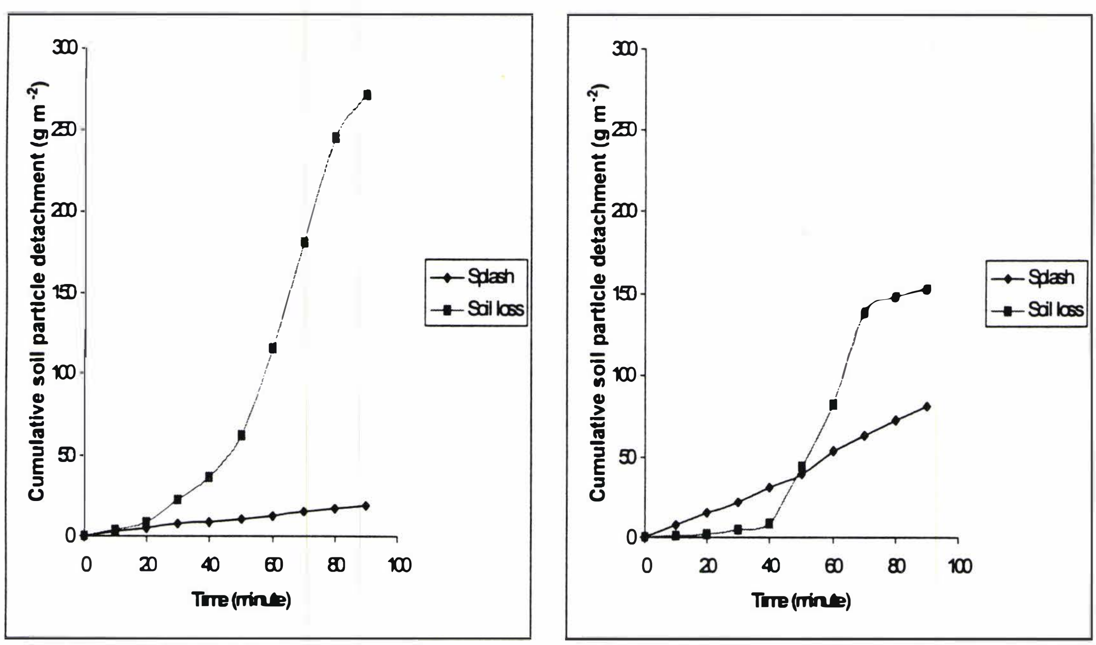


Figure 10.4 Cumulative soil particle detachment showing splash-soil loss relationships: (a) splash is smaller than soil loss on severely eroded Planosols; and (b) splash-soil loss ratio fluctuates on severely eroded Lixisols in rain 3.

(a) (b)

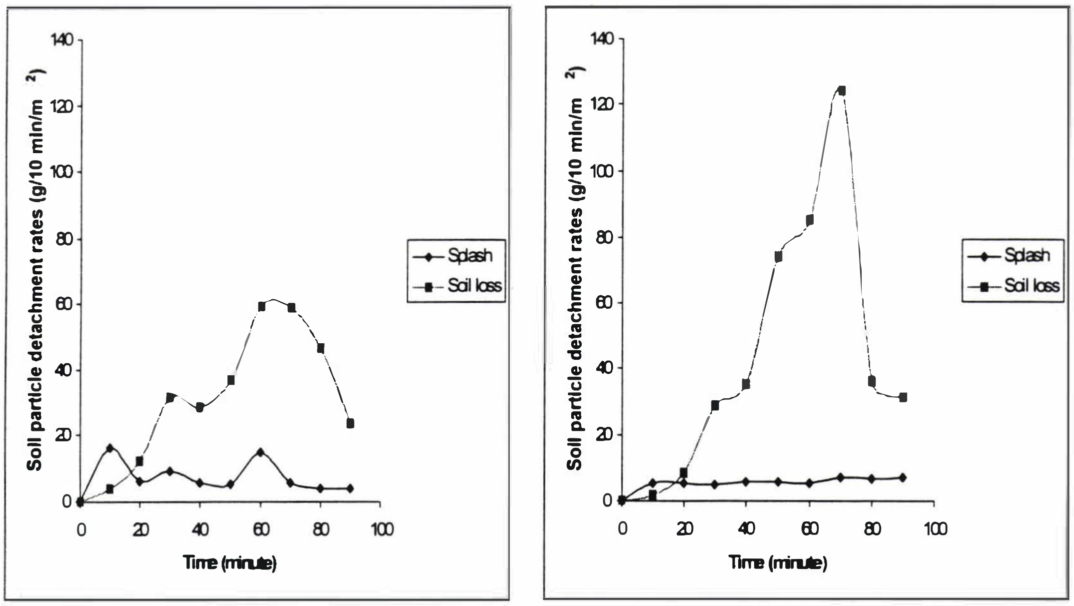


Figure 10.5 Temporal variations of soil particle detachment rates showing a short phase where splash is higher than soil loss and a long phase where splash is smaller than soil loss on (a) moderately eroded Vertisols, and (b) severely eroded Vertisols in rain 3.

(a)

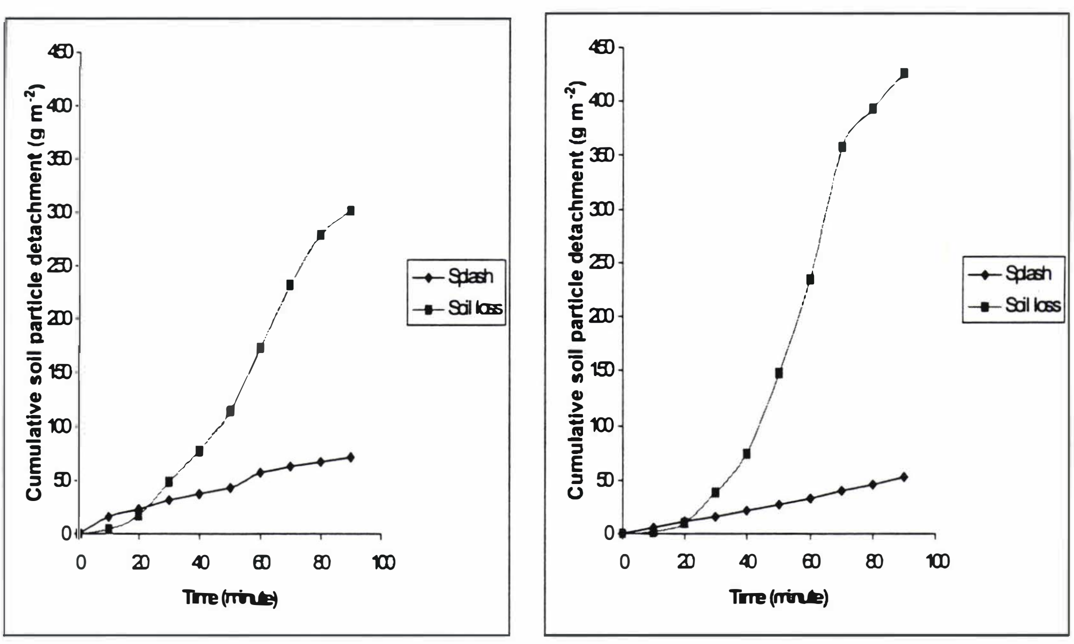


Figure 10.6 Cumulative soil particle detachment showing a short phase where splash is higher than soil loss and a long phase where splash is smaller than soil loss on (a) moderately eroded Vertisols, and (b) severely eroded Vertisols in rain 3.

(1) Splash detachment is higher than soil loss

Splash detachment rates are higher than soil loss rates on slightly eroded Lixisols, indicating that part of the splashed-off sediment was redistributed over the field, because the transport capacity of the sheet flow was lower than the detachment capacity of the raindrop impact (figures 10.1a and 10.2a). Overland flow did not occur on slightly eroded Lixisols, allowing all splashed-off sediment to be redistributed in the experimental plot. This is an evidence that raindrop detachment is a pre-requisite for interrill erosion and the amount of sediment contained in the runoff water depends on the availability of competent overland flow to transport it out of the catchment area.

(2) Splash detachment and soil loss have similar values

Splash detachment rates and soil loss rates display similar values on some moderately eroded Lixisols, indicating that the transport capacity of the overland flow equaled the detachment capacity of the raindrop impact (figures 10.1b and 10.2b). In fact, the dominant processes controlling soil loss were (1) the supply of sediment by raindrop detachment, and (2) the transport of splash-off sediment. The role of the surface flow under these circumstances is to transport the soil particles detached by raindrop impacts and not to detach soil particles from the soil surface aggregates, because its velocity is too low to cause shear erosion (Govers and Poesen, 1988; Parson et al., 1991; Parson and Abraham, 1992).

(3) Splash detachment is lower than soil loss

Splash detachment rates are smaller than soil loss rates on severely eroded Planosols, indicating that part of the sediment originates from the overland flow detachment (figures 10.3a and 10.4a). In general, interrill soil loss on these soils was a function of (1) the detachment by raindrop impacts, (2) the detachment by sheet flow, and (3) the transport of detached soil particles by sheet flow.

(4) Splash-soil loss ratio fluctuates

The splash-soil loss ratio changes from high splash-small soil loss at the early stage of the rain to small splash-high soil loss as the rain proceeds on severely eroded Lixisols, indicating that the source of sediment can change within a rainfall event (figures 10.3b and 10.4b). Moderately and severely eroded Vertisols exhibit similar behaviour (figures 10.5 and 10.6).

In summary, interrill erosion might involve one or all of the three following sub-processes: (1) splash detachment associated with sediment redistribution, showing splash higher than soil loss; (2) splash detachment associated with washing, splash and soil loss being similar; and (3) splash detachment associated with overland flow detachment and sediment transport, showing splash smaller than soil loss. Soil loss increases with increasing number of sub-processes at work in interrill erosion (table 10.1). Excess rainfall enhances the dissipation of the raindrop energy, causing splash detachment to decrease (figure 10.7), whereas the scouring power of the overland flow increases and causes sheet flow detachment when the shear resistance of the soil surface aggregates is exceeded (figures 10.8 and 10.9). This is an evidence that splash erosion alone is not a good index of interrill erosion for some soils (Bradford and Huang, 1993; Wainwright, 1996).

Table 10.1 Correlation between soil loss and interrill sub-processes

Soil types	Erosion class	Plot	Rain 2		Rain 3		Dominant interrill sub-processes and splash-soil loss relationships
			Splash (g/m^2)	Soil loss (g/m^2)	Splash (g/m^2)	Soil loss (g/m^2)	
Lixisols	Slight	7	154	63	103	42	Splash and sediment redistribution: splash > soil loss
Vertisols	Slight	6	55	0	74	0	
Cambisols	Slight	23	39	0	52	33	
Fluvisols	Slight	9	153	57	117	82	
Fluvisols	Moderate	22	123	28	93	46	
Lixisols	Moderate	18	52	55	49	34	Splash and wash: splash = soil loss
Lixisols	Moderate	14	105	142	91	226	Splash and overland flow detachment with sediment transport: splash < soil loss
Lixisols	Severe	19	47	72	34	158	
Vertisols	Moderate	17	56	123	72	431	
Cambisols	Moderate	20	59	229	62	710	
Cambisols	Severe	5	61	76	73	231	
Planosols	Slight	15	80	92	60	220	
Planosols	Severe	25	31	160	19	409	

(a) (b)

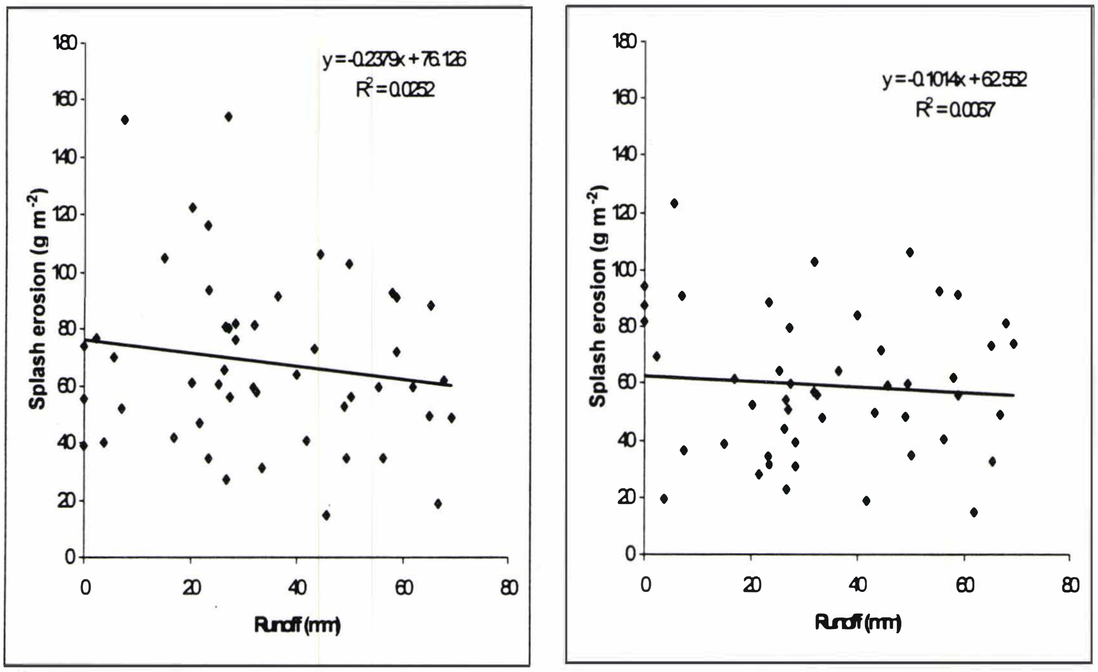


Figure 10.7 Relationships between runoff and splash erosion (a) from the initiation of the rain, and (b) from the initiation of runoff.

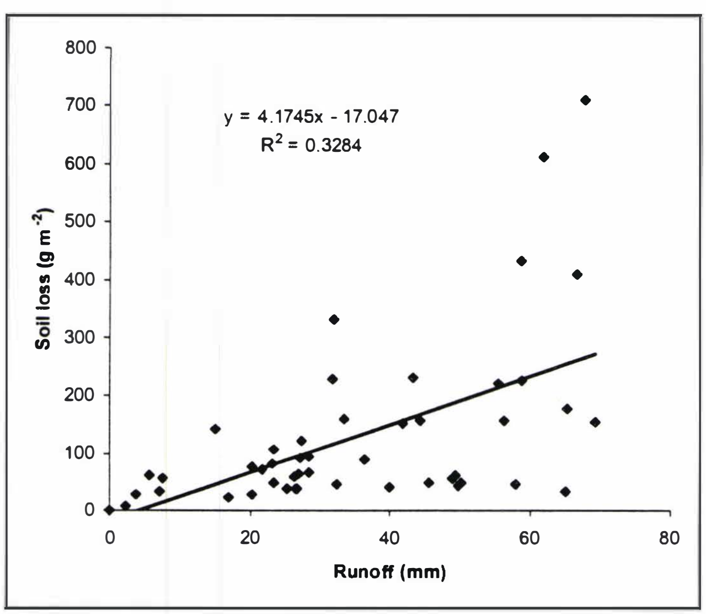


Figure 10.8 Relationship between runoff and soil loss.

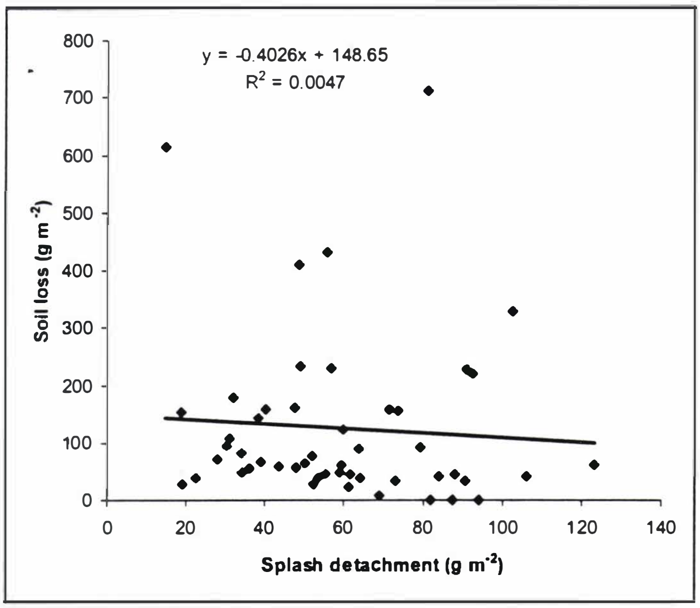


Figure 10.9 Relationship between splash detachment and soil loss.

10.1.2 Relationship between rains

The splash-soil loss ratio might vary or not between consecutive rain showers, revealing changes or not in sediment sources. For instance, splash detachment is higher than soil loss in rain 2, but smaller than soil loss in rain 3 on severely eroded Vertisols (figures 10.10 and 10.11). Slightly eroded Planosols and severely eroded Lixisols exhibit similar behaviour (figures 10.12 to 10.15). Splash detachment is equal to soil loss in rain 2 and higher than soil loss in rain 3 on moderately eroded Lixisols (figures 10.16 and 10.17). Despite substantial increase in rainfall intensities and durations during the third rain, the splash-soil loss ratio does not vary with time on slightly eroded Lixisols and severely eroded Planosols. While splash detachment remains higher than soil loss on the former, the later shows a situation where splash detachment is smaller than soil loss during both rain 2 and rain 3 (figures 10.18 to 10.21).

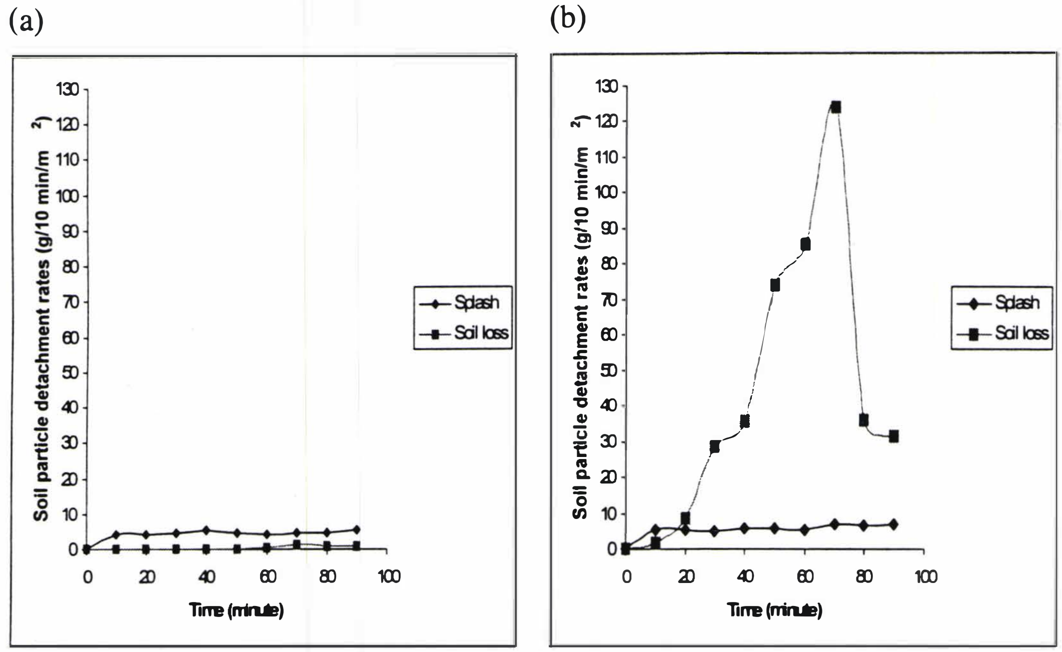


Figure 10.10 Soil particle detachment rates showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on severely eroded Vertisols.

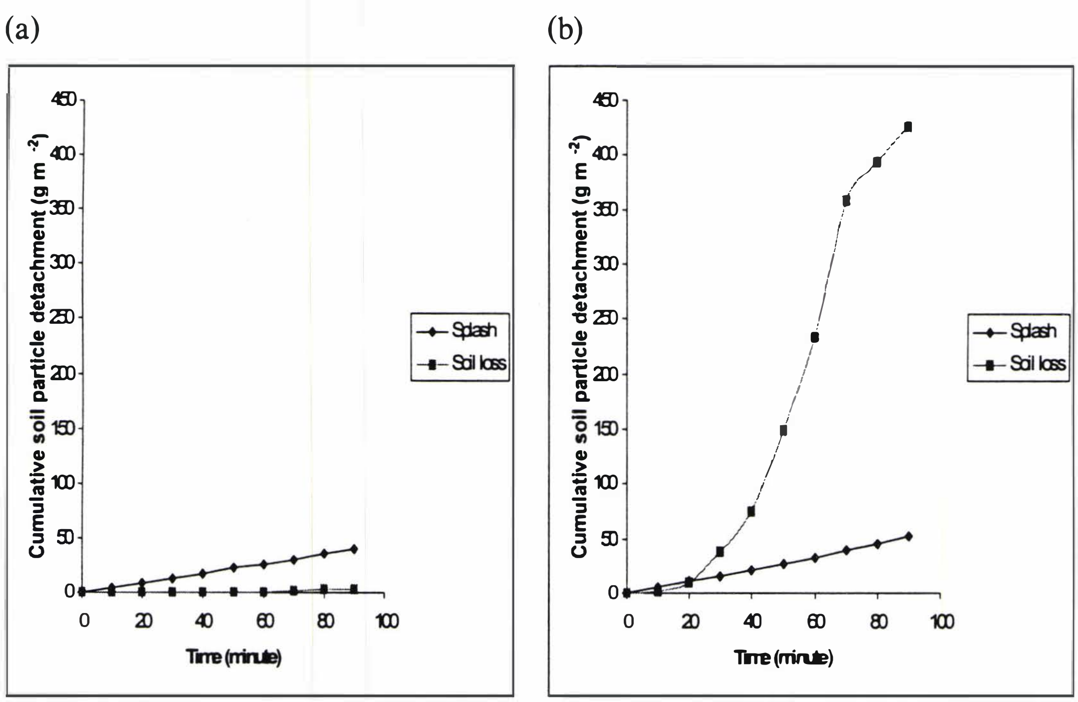


Figure 10.11 Cumulative soil particle detachment showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on severely eroded Vertisols.

(a) (b)

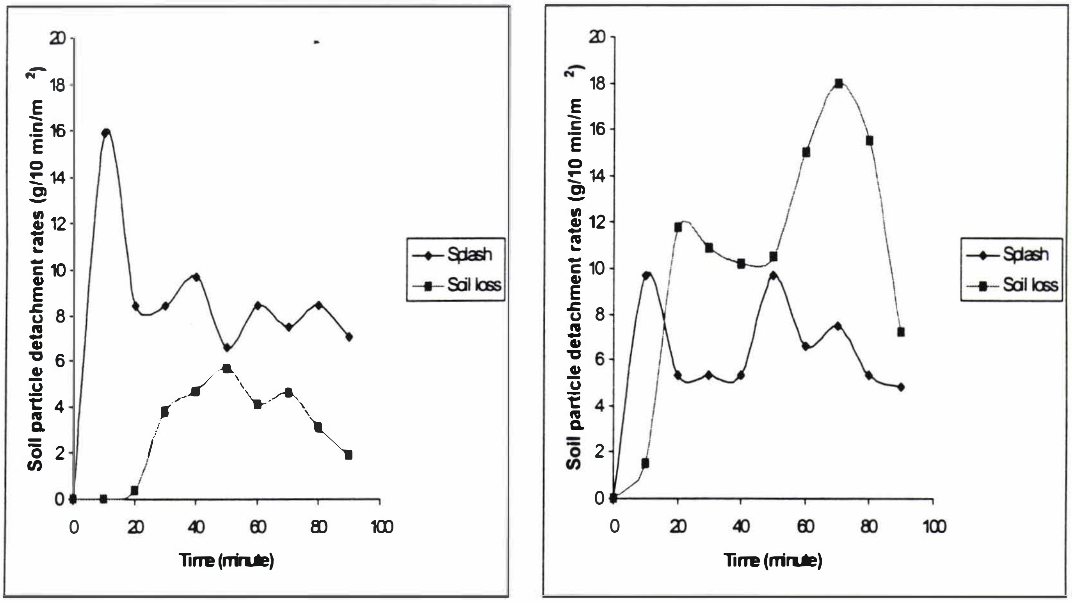


Figure 10.12 Soil particle detachment rates showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on slightly eroded Planosols.

(a) (b)

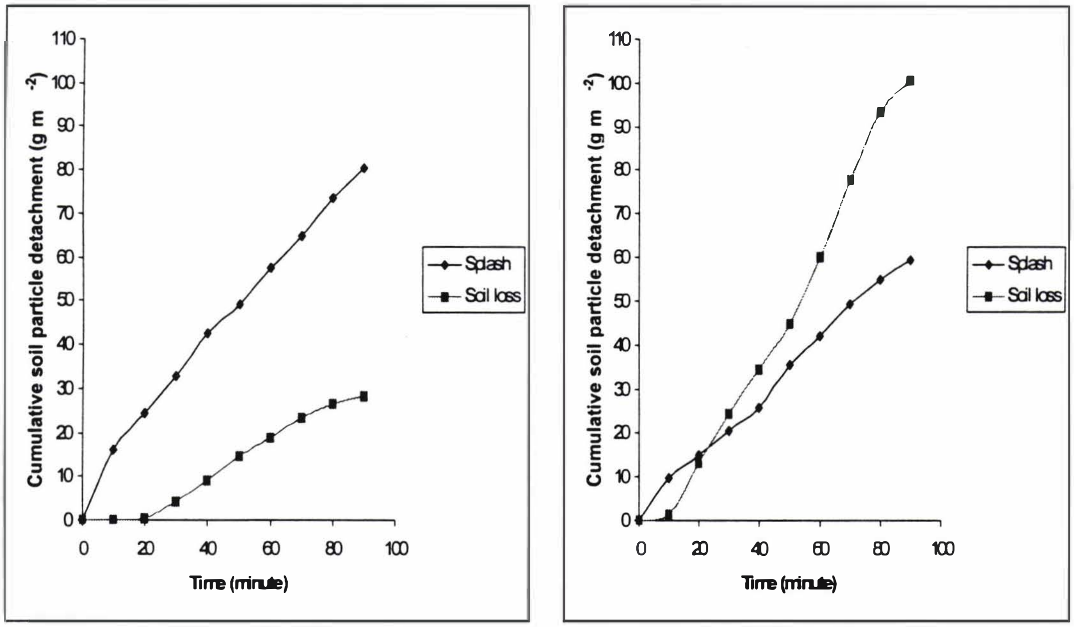


Figure 10.13 Cumulative soil particle detachment showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on slightly eroded Planosols.

(a) (b)

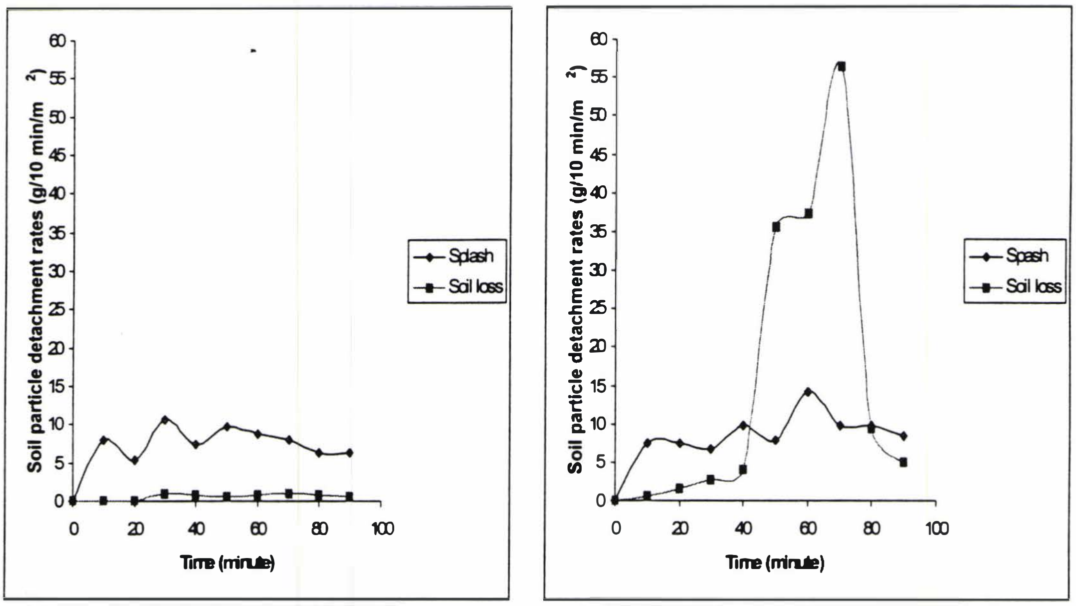


Figure 10.14 Soil particle detachment rates showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on severely eroded Lixisols.

(a) (b)

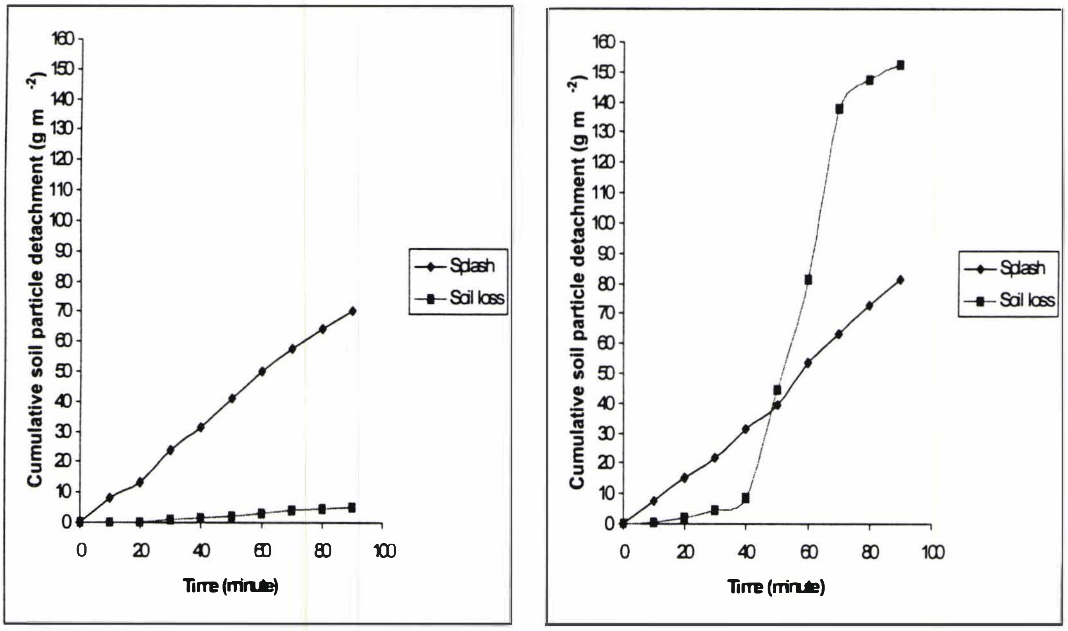


Figure 10.15 Cumulative soil particle detachment showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on severely eroded Lixisols.

(a) (b)

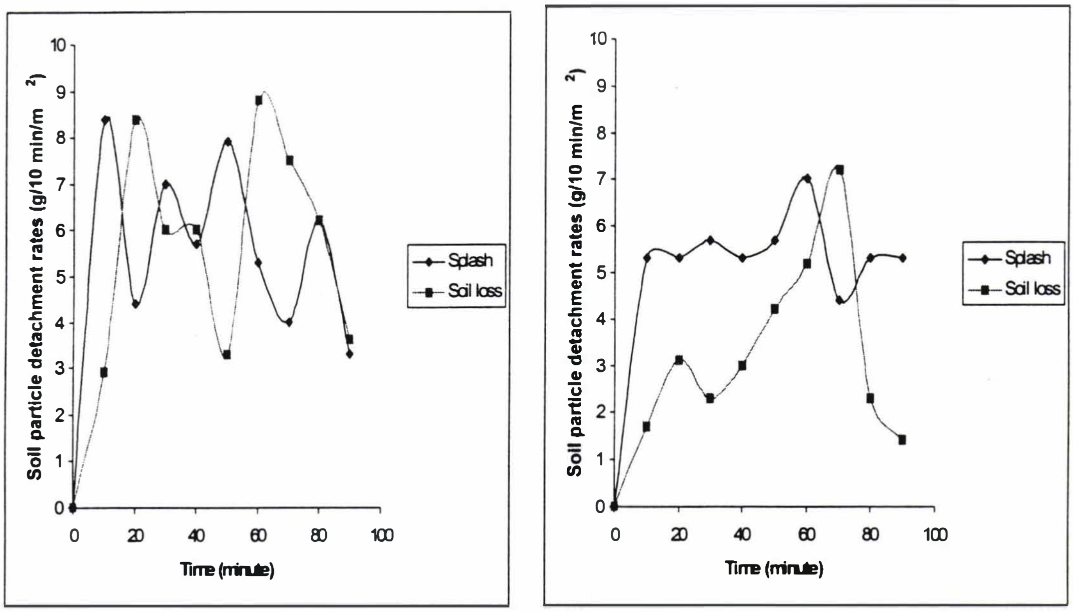


Figure 10.16 Soil particle detachment rates showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on moderately eroded Lixisols.

(a) (b)

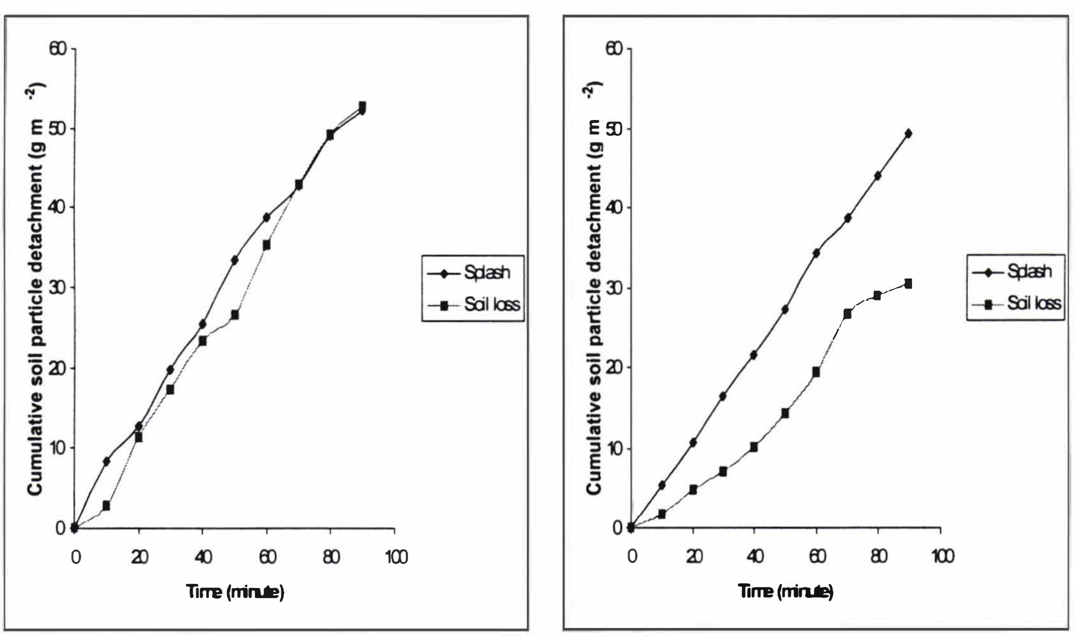


Figure 10.17 Cumulative soil particle detachment showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on moderately eroded Lixisols.

(a) (b)

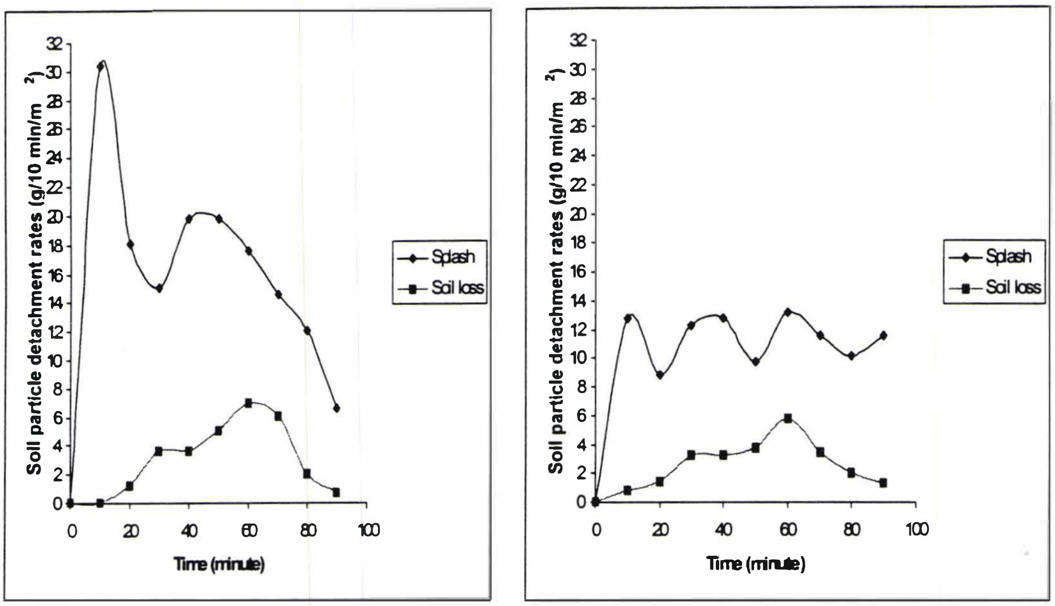


Figure 10.18 Soil particle detachment rates showing variations in the splash-soil loss relationships between rain 2 (a) and rain 3 (b) on slightly eroded Lixisols.

(a) (b)

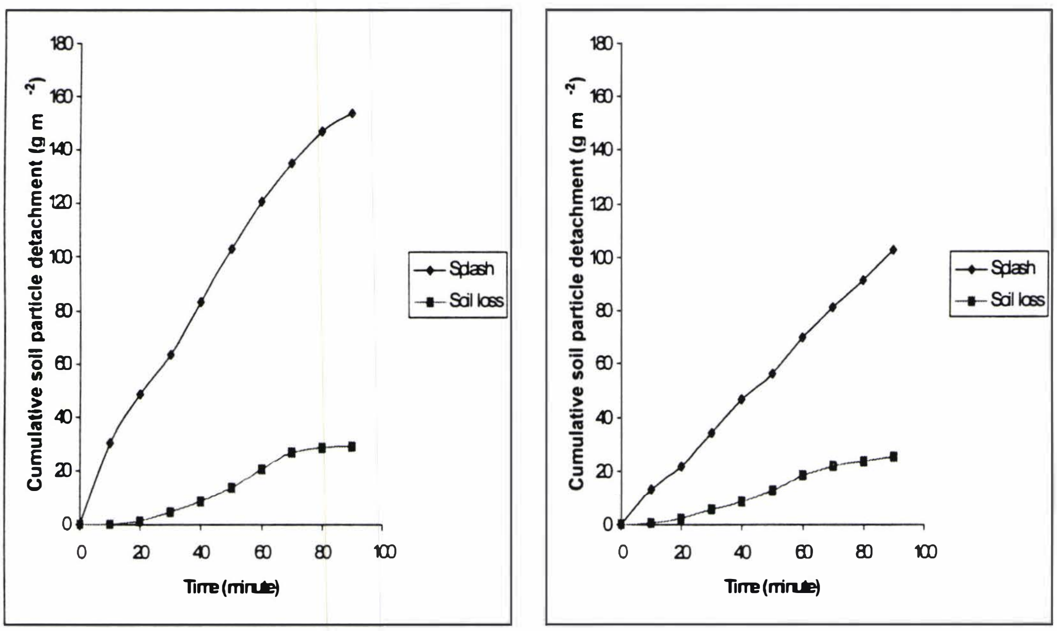


Figure 10.19 Cumulative soil particle detachment showing variations in the splash-soil loss relationships (splash is higher than soil loss) between rain 2 (a) and rain 3 (b) on slightly eroded Lixisols.

(a) (b)

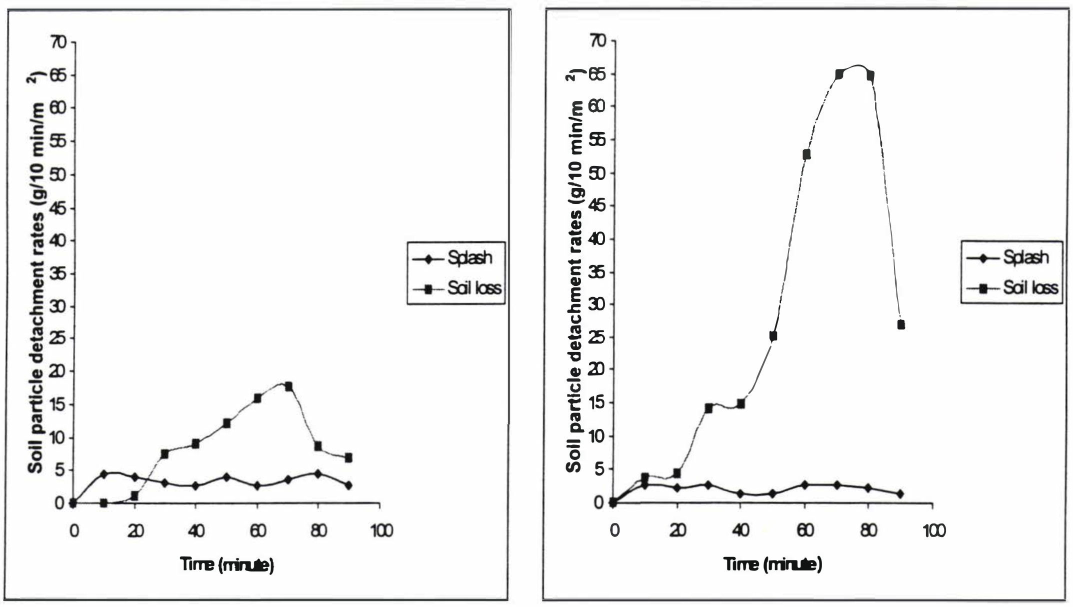


Figure 10.20 Soil particle detachment rates showing variation in the splash-soil loss relationships (splash is smaller than soil loss) between rain 2 (a) and rain 3 (b) on severely eroded Planosols.

(a) (b)

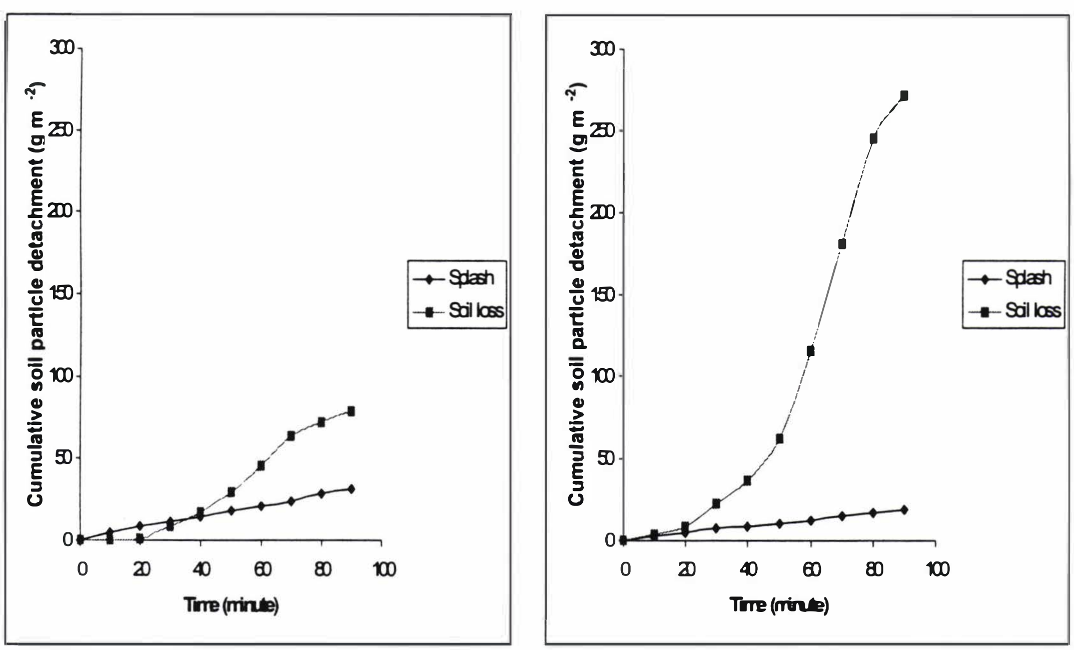


Figure 10.21 Cumulative soil particle detachment showing variations in the splash-soil loss relationships (splash is smaller than soil loss) between rain 2 (a) and rain 3 (b) on severely eroded Planosols.

In general, there is a tendency for many soils to exhibit single interrill processes (splash detachment associated with sediment redistribution) in rain 2 and complex interrill sub-processes (splash detachment, overland flow detachment associated with sediment transport) in rain 3 (table 10.2).

Table10.2 Variations of interrill sub-processes between rains

Type of dominant interrill sub-processes	**Number of plots (%)**	
	Rain 2	**Rain 3**
Splash detachment associated with sediment redistribution	8	4
Splash detachment associated with sediment transport	52	36
Splash detachment, overland flow detachment associated with sediment transport	40	60

10.2 RUNOFF, SOIL LOSS AND SOIL SURFACE RESISTANCE

Despite the similarity of rainfall characteristics in terms of intensities, durations and number of events between experimental plots, soil loss varies over considerable ranges. For instance, there is no soil loss on slightly eroded Vertisols, but 613 g/m^2 of soil loss was measured on severely eroded Vertisols in rain 3. Cambisols, Lixisols and Planosols display similar behaviour. The differential behaviour between soils can be attributed to the relative soil surface strength controlling cohesion and regulating structural stability of the aggregates (table 10.3). Soil loss increases with decreasing soil surface resistance and the positive intercept suggests the existence of a threshold soil surface resistance that was exceeded by flow shear strength to initiate overland flow detachment (figure 10.22), agreeing with the concept shared by models based on stream power theory (Huang, 1995).

Table 10.3 Variations of runoff, soil loss and soil surface resistance

Soil characteristics			Rain 2				Rain 3			
Soil types	**Erosion class**	**Plot**	**Shear strength (Pa)**		**Runoff (mm)**	**Erosion (g/m^2)**	**Shear strength (Pa)**		**Runoff (mm)**	**Erosion (g/m^2)**
			dry	**wet**			**dry**	**wet**		
Lixisols	Slightly eroded	7	1.7	1.3	27	63	1.9	1.7	50	42
	Moderately eroded	3	2.3	1.4	29	94	2.6	1.8	40	40
		4	1.5	0.8	17	22	2.0	1	36	88
		14	1.7	1.5	15	142	1.3	0.9	59	226
		18	2.6	2.0	49	55	2.9	2.4	65	34
		24	1.8	0.9	32	46	1.8	0.9	69	156
	Severely eroded	16	1.0	0.8	6	61	0.8	0.3	32	329
		19	1.0	0.7	22	72	1.0	0.9	56	158
Vertisols	Slightly eroded	6	1.2	1	0	0	1.1	0.8	0	0
	Moderately eroded	11	1.3	1	27	39	1.0	0.9	50	48
		17	1.1	0.7	28	123	0.7	0.1	59	131
	Severely eroded	21	0.4	0	4	28	0.2	0	62	613
Cambisols	Slightly eroded	2	2.0	1.6	2	7	2.1	1.2	23	47
		23	1.0	0.9	0	0	0.8	0.1	7	33
	Moderately eroded	10	2.2	1.7	25	37	1.9	1.4	49	62
		20	0.4	0	32	229	0.3	0	68	710
	Severely eroded	1	2.2	2	26	59	1.5	1.2	44	157
		5	1.6	1.1	20	76	1.3	0.9	43	231
Fluvisols	Slightly eroded	9	1.8	1.2	8	57	1.8	1.6	23	82
	Moderately eroded	22	2.2	1.7	20	28	2.2	1.8	58	46
Leptosols	Severely eroded	12	1.9	1.7	27	38	1.5	0.9	46	48
Planosols	Slightly eroded	15	2.7	1.7	27	92	2.4	1	56	220
	Moderately eroded	13	2.3	2	29	66	2.3	1.2	65	179
	Severely eroded	8	1.1	1	23	107	2.1	1.2	42	153
		25	0.5	0.3	34	160	0.7	0.1	67	409

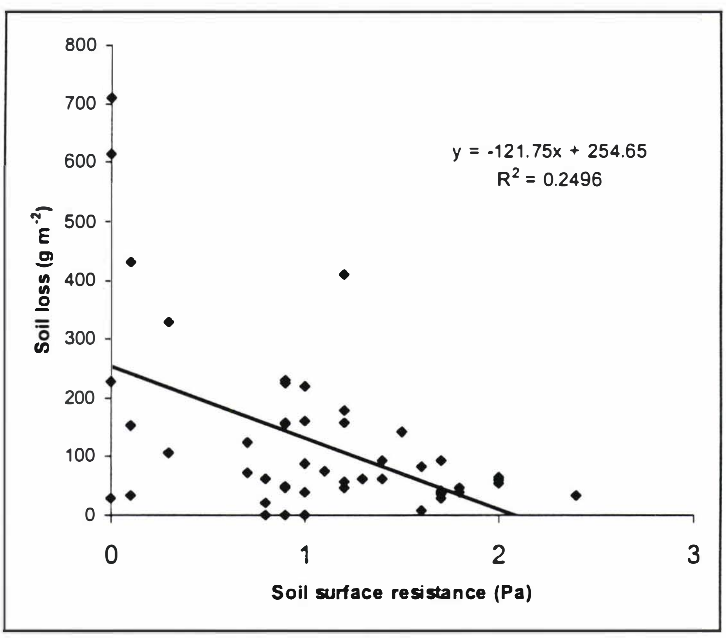


Figure 10.22 Relationship between soil surface resistance and soil loss.

Soil surface resistance is higher under dry conditions than under wet conditions. This can be attributed to the fact that, on drying, the relatively small soil particles (clay, oxides and organic matter) move towards the points of contact between relatively large soil particles. On slightly eroded Lixisols, the soil surface resistance increased with time, indicating compacting and cementing effects that enhance cohesion and increase shear strength (Gerlach, 1953).

10.3 RUNOFF, SOIL LOSS AND SOIL SURFACE ROUGHNESS

Interactions among runoff, soil loss and soil surface geometry as affected by erosion, deposition and consolidation processes, evidence four soil surface conditions, including (1) crusting soil surface; (2) denudational soil surface; (3) micro-rilling soil surface; and (4) swelling soil surface (table 10.4).

Table 10.4 Interactions among runoff, soil loss and soil surface roughness

Soil types	Erosion classes	Treat-ment	Roughness indices		Runoff (mm)	Erosion (g/m^2)	Dominant soil surface conditions
			Standard deviation (mm)	Nugget (mm^2)			
Lixisols	Slightly eroded	a	7.5	34	-	-	Crusting
		b	6.3	11	27	64	
		c	6.6	4	50	42	
	Moderately eroded	a	9.5	43	-	-	
		b	5.6	14	49	54	
		c	5.9	11	65	34	
Vertisols	Moderately eroded	a	11	99	-	-	Denudation
		b	8.8	35	28	123	
		c	6	15	59	431	
	Severely eroded	a	12.6	115	-	-	
		b	12.9	134	4	28	
		c	9.7	58	62	613	
Cambisols	Moderately eroded	a	13.7	135	-	-	
		b	9.6	43	32	229	
		c	7.7	29	68	710	
	Severely eroded	a	9.3	42	-	-	
		b	7.7	6	26	59	
		c	7.5	4	44	157	
Fluvisols	Slightly eroded	a	11	55	-	-	
		b	9.5	10	8	56	
		c	8.6	2	23	82	
Planosols	Slightly eroded	a	6.8	41	-	-	
		b	5.2	23	27	92	
		c	4.7	4	57	220	
Lixisols	Severely eroded	a	8.4	138	-	-	Micro-rilling
		b	10.9	50	6	61	
		c	12.8	96	32	330	
Vertisols	Slightly eroded	a	16.9	258	-	-	Swelling
		b	15.7	218	0	0	
		c	19.5	369	0	0	

a = after ploughing; b = after first rain subsequent to ploughing; c = after second rain.

Experimental plots for each soil surface condition were stratified into classes of erosion depth and deposition depth through linear interpolation using the kriging technique. Their boundaries were mapped to highlight spatial variations in composition within the area of interest. Classes were defined in gradual change to form gradient. Positive gradients show areas of erosion, negative gradients show areas of deposition and zero gradients show areas of transport or transit of detached sediment.

10.3.1 Crusting soil surface

(1) Variations of interrill erosion indicators

The process of crusting is characterized by an increased runoff and a decrease of both soil loss and soil surface roughness with increasing rainfall characteristics for the showers subsequent to initial ploughing. The differences in response suggest that two processes blocking infiltration and particle detachment have taken place simultaneously at the soil surface during the simulated rains. Firstly, an increase of soil moisture in the topsoil layer and the filling of microtopographic depressions at the soil surface accelerate the circulation of the overland flow. Secondly, crusts are layers that have a greater density, higher shear strength and lower saturated hydraulic conductivity. This decreases particle detachment, restricts infiltration and enhances runoff. The consequence of this is that later runoff behaviour expresses mainly rainfall characteristics.

A higher runoff accompanied with a small soil loss indicates that the resistance of the soil surface aggregates exceeded the erosive power of the raindrop impacts and surface flow. The soil surface roughness did no longer have random orientation after the first rain subsequent to ploughing. Interrill erosion operated in a "low detachment-high transport system".

(2) Spatial distribution of erosion and deposition areas

Crusted soil surfaces show a decrease of the size and gradient of erosion and deposition zones with increasing rainfall characteristics. In both the second rain and the third rain, erosion zones exhibit a larger coverage and a higher gradient than deposition zones.

Erosion zones occupy about 75% of the total area in the second rain and less than 50% of the total area in the third rain. Erosion depth varies from 10 to 36 mm after rain 2 and from 6 to 18 mm after rain 3. Deposition areas show a maximum depth of 20 and 18 mm after rain 2 and rain 3, respectively. Erosion areas occupy mainly the upper part of the plot, while deposition areas are dominant downslope. Parallel orientations of flat and smooth paths correspond to sheet flow areas under crusting conditions. Also, the early runoff generation observed on slightly and moderately eroded Lixisols indicates slow soil permeability. Crusting soil surfaces consist mainly of large areas of transport (figures 10.23 and 10.24). Kazman et al. (1983), Bradford et al. (1987), Casenave and Valentin (1989), Moore and Singer (1990) and Levy (1994) report similar results.

(a) (b)

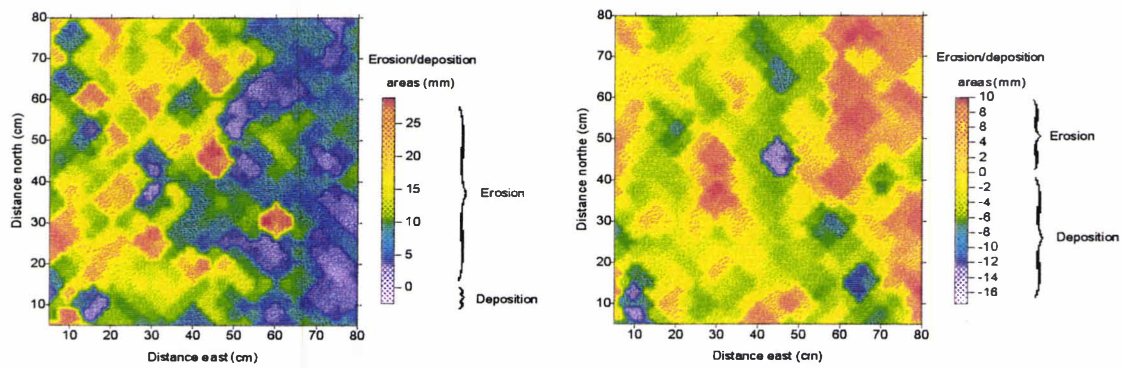


Figure 10.23 Erosion and deposition areas on crusting soil surface on slightly eroded Lixisols (a) after rain 2, and (b) after rain 3.

(a) (b)

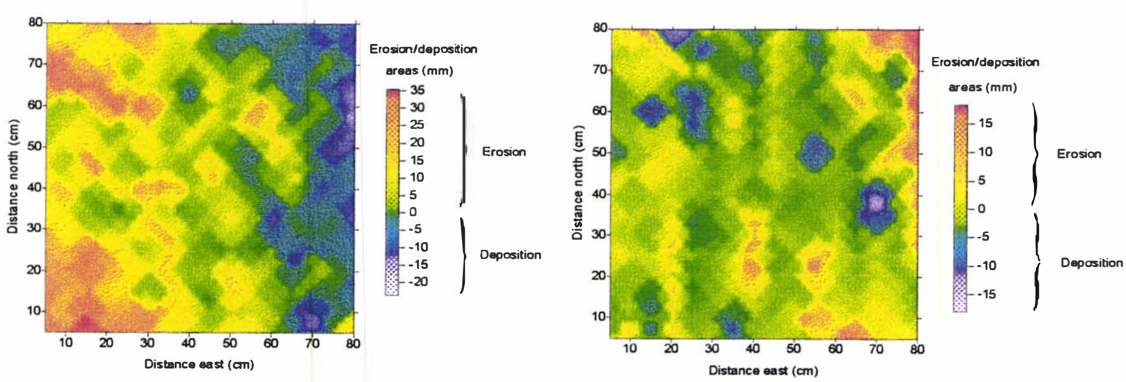


Figure 10.24 Erosion and deposition areas on crusting soil surface on moderately eroded Lixisols (a) after rain 2, and (b) after rain 3.

10.3.2 Denudational soil surface

(1) Variations of interrill erosion parameters

In the denudation process, both runoff and soil loss increase significantly, whereas the soil surface roughness decreases with increasing rainfall characteristics for the rain showers subsequent to initial ploughing. A decrease of the soil surface roughness indicates the flattening of the soil surface. Increased soil loss accompanied with a decreased soil surface roughness reflects the removal of fairly uniform soil layers after the initial surface roughness subsequent to ploughing has decreased.

(2) Spatial distribution of erosion and deposition areas

Denudation surfaces display large regions of erosion (positive values) covering more than 50% of the total area. They were observed on many soils, including moderately eroded Vertisols, severely eroded Vertisols, slightly eroded Planosols, moderately eroded Cambisols, severely eroded Cambisols, and slightly eroded Fluvisols (figures 10.25 to 10.30).

Erosion zones increased from about 50% after rain 2 to 70% after rain 3 and erosion depth increased from 30 to 46 mm, respectively. The location of erosion and deposition areas varied from rain to rain and from soil to soil. For many soils, erosion and deposition areas were scattered all over the experimental plot. For moderately eroded Vertisols, erosion zones were mainly located on the upper part of the experimental plot, whereas deposition areas concentrated in the lower part of the plot after the second rain. But after the third rain, the location of erosion and deposition areas was reversed. Large deposition areas at the lower part of the experimental plot after rain 2 are evidence that the supply of detached sediment exceeded the capacity of the overland flow to transport it. This is a clue that the amount of detached sediment that is eroded depends on the availability of competent overland flow to transport it. Changes in location and coverage of the erosion and deposition areas between consecutive rains reflect a transformation from a "high detachment-low transport system" in the second rain to a "high detachment-high transport system" in the third rain.

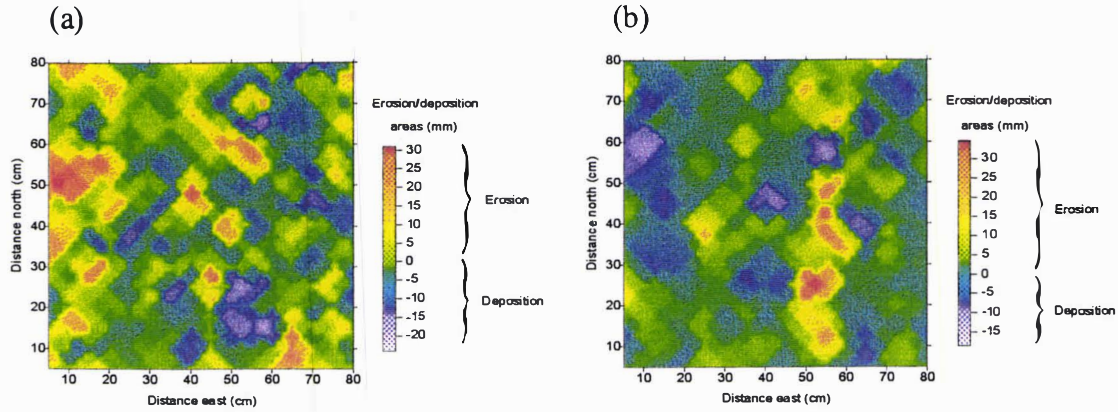


Figure 10.25 Erosion and deposition areas on denudation soil surface on moderately eroded Vertisols (a) after rain 2, and (b) after rain 3.

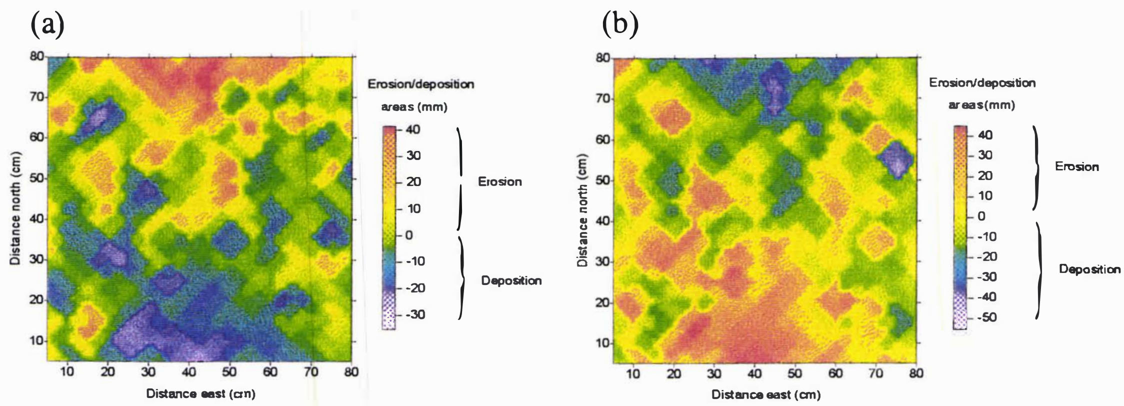


Figure 10.26 Erosion and deposition areas on denudation soil surface on severely eroded Vertisols (a) after rain 2, and (b) after rain 3.

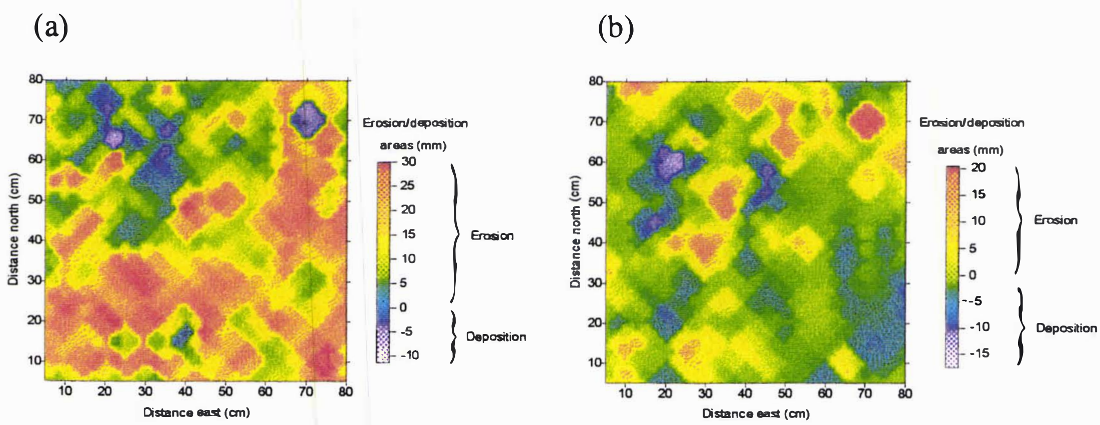


Figure 10.27 Erosion and deposition areas on denudation soil surface on slightly eroded Planosols (a) after rain 2, and (b) after rain 3.

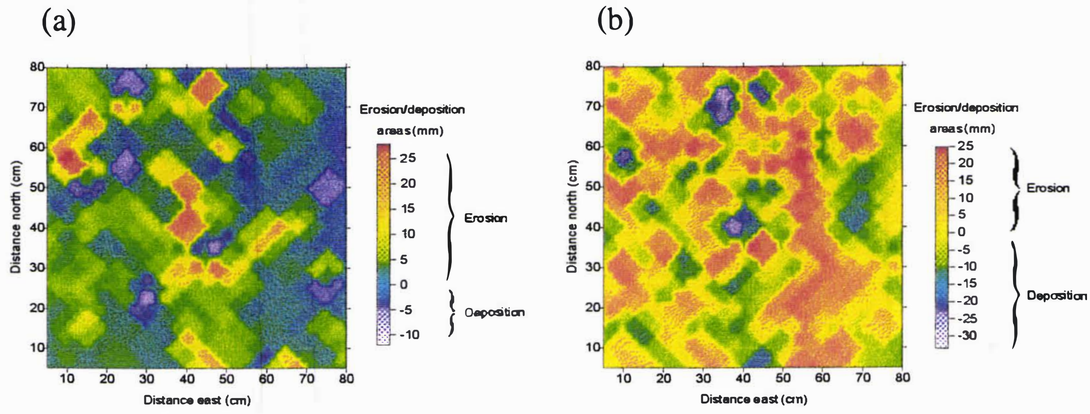


Figure 10.28 Erosion and deposition areas on denudation soil surface on moderately eroded Cambisols (a) after rain 2, and (b) after rain 3.

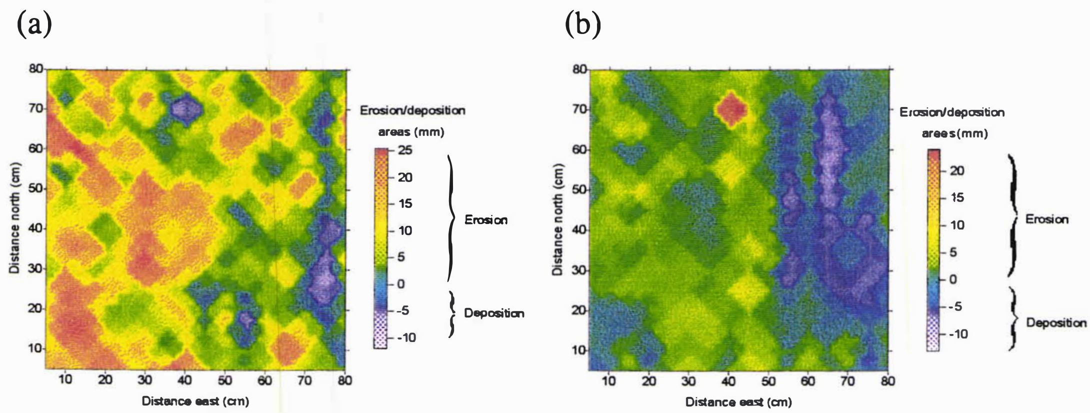


Figure 10.29 Erosion and deposition areas on denudation soil surface on severely eroded Cambisols (a) after rain 2, and (b) after rain 3.

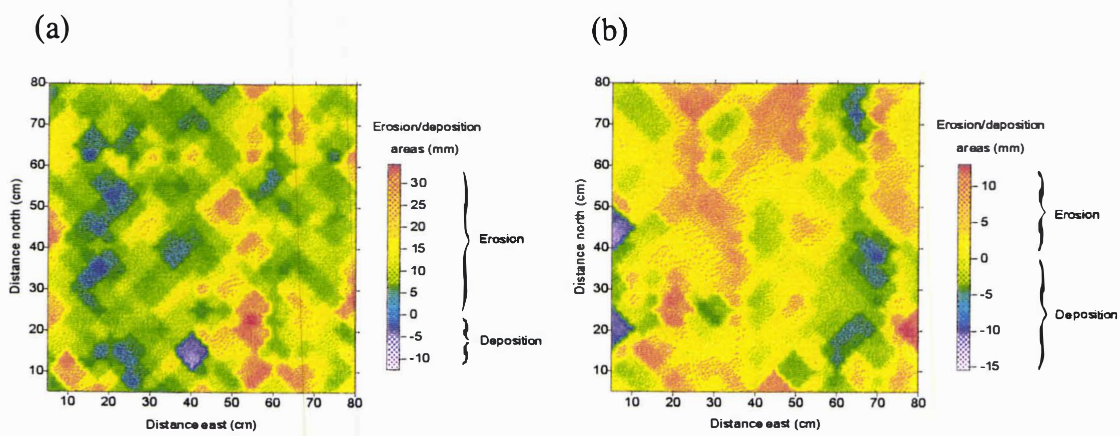


Figure 10.30 Erosion and deposition areas on denudation soil surface on slightly eroded Fluvisols (a) after rain 2, and (b) after rain 3.

10.3.3 Micro-rilling soil surface

(1) Variations of interrill erosion parameters

The process of micro-rilling is characterized by a substantial increase in runoff, a substantial increase in soil loss, and an increasing soil surface roughness, with increasing rainfall characteristics for the rain showers subsequent to initial ploughing. A decrease of the nugget values between ploughing and rain 2 may indicate that the rainfall availability was a limiting factor. An increase in the values of all interrill erosion parameters indicates that many erosion processes have taken place either simultaneously or successively.

(2) Spatial distribution of erosion and deposition areas

Ponded water caused by increased roughness protects the soil surface from raindrop impacts, reducing sealing and delaying runoff and soil erosion. But, increased runoff concentration in the micro-depressions enhances erosion by intermittent micro-channels and deposition from side wall collapse, causing alternating linear zones of erosion and deposition (figure 10.31). Both incision and denudation play a role in micro-rilling (Helming and Römkens, 1996).

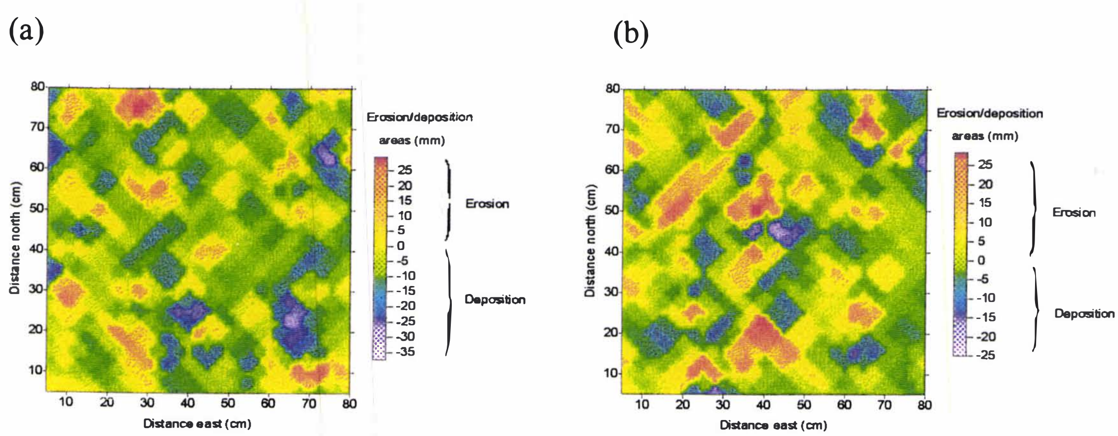


Figure 10.31 Erosion and deposition areas on micro-rilling soil surface on severely eroded Lixisols (a) after rain 2, and (b) after rain 3.

10.3.4 Swelling (clod expansion) soil surface

Despite a substantial increase of rainfall characteristics in terms of intensity, duration and number of events, the plot on slightly eroded Vertisols did not produce runoff and soil loss. But the soil surface roughness increased significantly for the rain showers subsequent to initial ploughing, which indicated swelling of the soil surface aggregates.

10.4 CONCLUSION

The interactions among interrill soil erosion indicators vary and this influences the variation of the soil surface elevation points between consecutive rains. The rate of decrease of the elevation points influences the distribution of the erosion features on the relief. This permits to know the extent of erosion on each experimental plot and the extent of deposition at other locations without reaching the outlet of the experimental plot. In other words, the study shows that the experimental plots are not "black boxes" in which one does not know what is happening inside. Similarly, soil loss changes according to processes that affect soil surface conditions. The order of increasing relative susceptibility to soil erosion is indicated by swelling soil surface < crusting soil surface < micro-rilling soil surface < denudational soil surface.

Monitoring changes in the soil surface roughness allows updating the resistance of the soil surface, which improves the assessment of interrill erosion. The study of the soil surface microtopography at micro-plot scale allows to predict erosion features at plot scale, defined by type and intensity, along the relief, with respect to soil characteristics, topography, land use and management practices. At plot scale, small soil surface roughness decrease may cause pronounced erosion features only downslope. Soil surface aggregates susceptible to liquefaction display high decrease of the soil surface roughness, generating erosion features all over the relief. On soil surfaces reflecting the presence of swelling clays (smectites), complete expansion of the soil surface aggregates due to saturation is required before substantial decrease of the soil surface elevation points starts.

CHAPTER 11

DEVELOPMENT OF A LOCAL MODEL OF INTERRILL SOIL EROSION

In this chapter, a local interrill soil erosion model is developed. The structure of the model is based on the mechanisms of detachment and transport of soil particles. It predicts soil loss on a rainfall event basis with higher accuracy than the interrill soil erosion model developed by Kinnell (1991).

11.1 CONCEPTUAL STRUCTURE

Many interrill erosion models have been developed. The current ones are:

$E = K_{ii}I^2$ (Meyer and Harmon, 1989), (1)

and

$E = K_{iq}Iq$ (Kinnell,1991), (2)

where E is the interrill erosion rate, K_{ii} and K_{iq} are interrill erodibility parameters, I is average rainfall intensity, and q is average runoff rate.

These equations do not represent the individual processes of detachment by splash and flow. Based on the interactions among interrill erosion parameters observed during the experiments, an equation representing both splash detachment and overland flow detachment can be written as:

$E = E_s + E_f$ (3)

where E is interrill soil loss, E_s is splash detachment and E_f is flow detachment.

11.1.1 Expression of splash detachment

From the equation (3), let E_s and E_f represent detachment by splash and detachment by flow, respectively. Data indicated that splash detachment was related to rainfall and runoff characteristics. A mathematical expression describing splash variations with variations in rainfall characteristics and runoff characteristics is proposed as follows:

$$E_s = K_l\left(\frac{P-Q}{2}\right)^2 \quad (4)$$

which can be re-written as:

$$E_s = K_I \frac{(P-Q)^2}{4} \qquad (5)$$

where E_s is splash rate in kg h^{-1} m^{-2}; K_I is interrill soil erodibility parameter in kg s^{-1} m^{-4}; P is average rainfall in mm; and Q is average runoff in mm.

In the equation (5), the erosivity of raindrops to detach soil particles is related to the squared half difference between rainfall and runoff multiplied by the interrill soil erodibility parameter. Basically, the form of the splash equation resembles that of the kinetic energy developed by Laws (1941), and Gunn and Kinzer (1949):

$E = 1/2mV^2$, where m is the mass and V is the velocity.

The equation (5) shows that the variations in splash detachment are closely related to changes in rainfall and runoff characteristics. The effective rainfall hitting the soil surface aggregates and causing particle detachment is the difference between rainfall and runoff. Splash detachment decreases with increasing runoff and is maximal when runoff equals zero, agreeing with the investigation results.

11.1.2 Expression of overland flow detachment

The experiment results showed that detachment by flow is positively correlated to runoff and negatively correlated to the soil surface resistance. A mathematical expression describing variations in overland flow detachment with variations in rainfall and runoff characteristics and with soil surface resistance can be written as:

$$E_f = K_I \frac{PQ}{Exp^s} \qquad (6)$$

where E_f is detachment rate by flow in kg h^{-1} m^{-2}; K_I is interrill soil erodibility parameter in kg s^{-1} m^{-4}; P is average rainfall in mm; Q is average runoff in mm; and s is soil surface resistance in Pa.

From equation (6) it follows that overland flow detachment is expressed as a function of rainfall, runoff and soil surface resistance. The detachment by overland flow is positively correlated to rainfall and runoff and inversely correlated to the soil surface resistance.

11.1.3 Expression of interrill soil erosion

The interrill soil erosion is controlled by the mechanisms of detachment and transport of soil particles in the interrill areas. A mathematical expression integrating the fundamental interrill erosion sub-processes, including (1) detachment by splash, (2) detachment by overland flow, and (3) transport by overland flow, can be proposed as:

$$E = Es + Ef \Leftrightarrow E = K_I\frac{(P-Q)^2}{4} + K_I\frac{PQ}{Exp^s} \qquad (7)$$

or

$$E = K_I\left(\frac{(P-Q)^2}{4} + \frac{PQ}{Exp^s}\right) \qquad (8)$$

where E is interrill erosion rate in kg h^{-1} m^{-2}; P is rainfall in mm; Q is runoff in mm; K_I is interrill erodibility parameter in kg s^{-1} m^{-4}; and s is soil surface resistance in Pa.

It appears from the equation (8) that, when runoff (Q) tends to zero, then the dominant interrill sub-process is splash detachment and, when runoff (Q) equals rainfall (P), splash erosion is negligible and soil loss tends to originate mainly from overland flow detachment, agreeing with the investigation results. The magnitude of soil loss depends on the variations of runoff due to differences in soil properties, that control permeability and regulate infiltration and percolation. Soil loss also depends on the properties that govern stability of the soil surface aggregates. For instance, an increase of soil surface resistance caused by crust formation reduces detachment by sheet flow. In the meantime, crust formation causes an increase of runoff depth, enhancing the erosive power of the flowing water. Subsequently, interrill soil erosion calculated from the equation (8) is expressed as a function of rainfall, runoff and soil surface resistance.

The amounts of interrill soil loss may vary considerably according to the slope length and slope gradient, suggesting that the slope factor must be integrated in the equation (Bryan, 1979; Ben-Hur et al., 1992; Truman and Bradford, 1993). An appropriate expression of the local model of interrill soil erosion is then:

$$E = K_I\left(\frac{(P-Q)^2}{4} + \frac{PQ}{Exp^s}\right)S_f \qquad (9)$$

where S_f represents the slope factor.

Explicitly, the equation (9) translates a dynamic process of soil detachment by splash, soil detachment by flow and transport by flow that occurs in interrill areas, along a slope.

11.2 RELIABILITY AND VALIDATION OF THE MODEL

There is no standard equation of interrill soil erosion. Interrill soil erosion models are defined by specific erosion equations and the variables in the equations are measured under field or laboratory conditions. The question is which model reflects consistently the reality on the field. The comparison between models can help select the best estimator of interrill soil loss. For that purpose, a comparison between the Kinnell model and the local model of interrill erosion was made.

11.2.1 Efficiency of the interrill soil erosion equations

The following interrill soil erosion equations were compared:

$$E = K_{iq}Iq \text{ (Kinnell,1991)} \tag{10}$$

$$E = K_l\left(\frac{(P-Q)^2}{4} + \frac{PQ}{Exp^s}\right) \text{ (local model)} \tag{11}$$

To obtain simpler expressions, let us consider D1 = Iq and D2 = $\left(\frac{(P-Q)^2}{4} + \frac{PQ}{Exp^s}\right)$,

where I is average rainfall intensity in mm h^{-1}; q is average runoff rate in mm h^{-1}; P is average rainfall amount in mm; Q is average runoff amount in mm ; and s is soil surface resistance in Pa.

The equations (10) and (11) become respectively:

$$E = K_{iq}D1 \tag{12}$$

$$E = K_lD2 \tag{13}$$

The comparison between the two equations was not confined to highlighting the difference between D1 and D2 (table 11.1). It also allowed to observe if the variation of soil loss (E) was more related to the variation of D1 or D2. For each of the twenty-five experimental plots and for each simulated rain shower, D1 and D2 are calculated on an hourly basis, producing a set of 50 data for each term. The results of regression analysis applied to these data sets showed that D1 and D2 influence the estimates of soil loss in different ways (table 11.2).

Table 11.1 Values of D1 and D2 for each experimental plot and for each rain

Soil characteristics			Rain 2		Rain 3	
Soil types	**Erosion classes**	**Plot**	**D1 (mm^2)**	**D2 (mm^2)**	**D1 (mm^2)**	**D2 (mm^2)**
Lixisols	Slightly eroded	7	724	374	1660	480
	Moderately eroded	3	760	352	1330	478
		4	460	483	1215	773
		14	400	378	1965	967
		18	1308	221	2175	268
		24	864	496	2315	1077
	Severely eroded	16	152	469	1065	1243
		19	580	392	1880	944
Vertisols	Slightly eroded	6	0	473	0	804
	Moderately eroded	11	712	452	1675	895
		17	732	557	1975	2101
	Severely eroded	21	100	530	2065	2402
Cambisols	Slightly eroded	2	64	453	780	491
		23	0	473	240	921
	Moderately eroded	10	676	311	1645	608
		20	852	1050	2265	2602
	Severely eroded	1	704	272	1480	464
		5	544	555	1445	849
Fluvisols	Slightly eroded	9	204	435	775	604
	Moderately eroded	22	540	332	1935	447
Leptosols	Severely eroded	12	716	306	1525	864
Planosols	Slightly eroded	15	728	304	1855	875
	Moderately eroded	13	760	262	2180	792
	Severely eroded	8	624	446	1395	687
		25	892	859	2225	2331

Table 11.2 Regression between soil loss and D1 and D2 terms

Parameters	R	R^2	P-value
D1	0.552370	0.30511	3.1974E-05
D2	0.840494	0.70643	2.27E-14
D1D2	0.846951	0.71732	1.27E-13

The contribution of D2 in the prediction of soil loss is higher ($R^2 = 0.706$) than that of D1 ($R^2 = 0.305$), indicating that D2 explains about 71% of the variations in soil loss, whereas D1 explains only about 31% of the variations in soil loss. Similarly, the P-value is smaller for D2 (2.27E-14) than for D1 (3.1974E-05), suggesting that there is a closer relationship between soil loss and D2. Regression analysis between soil loss and D1 and D2 together shows values of 0.71732 and 1.27E-13 for R^2 and P-value, respectively. The similarity of results between D2 and D1D2 together confirms the efficiency of D2 for soil loss prediction. The correlation coefficient between D1 and D2 is 0.5537, indicating that D1 and D2 are positively related.

11.2.2 Determination of the interrill soil erodibility from the equations

Interrill soil erodibility values for each experimental plot and each simulated rain were calculated from K_{iq} = E/Iq using the Kinnell model (1991) and K_l = $E/(\frac{(P-Q)^2}{4} + \frac{PQ}{Exp^s})$ using the local model. Results show that there are similarities and differences between the local and the Kinnell interrill soil erosion models (tables 11.3 to 11.5).

Table 11.3 Interrill erodibility for each experimental plot and for each simulated rain

Soil characteristics			Rain 2		Rain 3	
Soil types	**Erosion classes**	**Plot**	**K_{iq}x10^{-4} (kg s^{-1} m^{-4})**	**K_Lx10^{-4} (kg s^{-1} m^{-4})**	**K_{iq}x10^{-4} (kg s^{-1} m^{-4})**	**K_Lx10^{-4} (kg s^{-1} m^{-4})**
Lixisols	Slightly eroded	7	161	312	47	162
	Moderately eroded	3	230	497	56	81
		4	91	86	135	212
		14	660	698	213	434
		18	79	465	29	238
		24	100	174	125	268
	Severely eroded	16	749	243	571	489
		19	230	340	155	309
Vertisols	Slightly eroded	6	0	0	0	0
	Moderately eroded	11	101	154	53	99
		17	311	409	122	115
	Severely eroded	21	528	100	550	473
Cambisols	Slightly eroded	2	217	31	110	175
		23	0	0	255	66
	Moderately eroded	10	103	224	69	187
		20	499	405	580	505
	Severely eroded	1	154	398	197	423
		5	260	255	296	504
Fluvisols	Severely eroded	9	517	243	197	253
	Moderately eroded	22	98	159	45	193
Leptosols	Severely eroded	12	97	227	58	103
Planosols	Severely eroded	15	233	557	220	467
	Moderately eroded	13	161	467	152	417
	Severely eroded	8	317	442	203	412
		25	333	346	341	325

K_{iq} and K_L are interrill erodibility parameters calculated from the Kinnell model (1991) and from the local model, respectively.

(1) Similarity between models

Differences in interrill soil erodibility values calculated from the Kinnell model and from the local model are attributed to differences in the structure of the models. However, the values of the interrill erodibility parameters tend to follow similar patterns. For instance, many plots show that interrill erodibility values might increase (severely eroded Vertisols), decrease (slightly eroded Lixisols) or remain constant (slightly eroded Vertisols) with increasing rainfall characteristics in terms of intensities, durations and number of events. For some slightly eroded soils, such as Vertisols, Lixisols and Planosols, the order of increasing interrill erodibility is slightly eroded Vertisols < slightly eroded Lixisols < slightly eroded Planosols. On Vertisols, interrill soil erodibility increases with increasing erosion severity (table 11.3).

(2) Differences between models

Soils were ranked according to the Kinnell and local interrill soil erosion models. The upper ranks indicate a high erodibility, whereas the lower ranks indicate a low erodibility. Differences between models are highlighted through the relationships between the ranks and interrill soil erosion parameters, producing advantages and disadvantages of the local interrill soil erosion model (tables 11.4 and 11.5).

Table 11.4 Ranking of the plots according to interrill erodibility values in rain 2

Soil characteristics			Erosion parameters		Kinnell model		Local model	
Soil types	Erosion classes	Plot	Runoff (mm)	Erosion (g/m²)	$K_{iq}x10^{-4}$ (kg s^{-1} m^{-4})	Rank (K_{iq})	$K_i x10^{-4}$ (kg s^{-1} m^{-4})	Rank (K_i)
Lixisols	Slightly eroded	7	27	63	161	14	312	12
	Moderately eroded	3	29	94	230	11	497	3
		4	17	22	91	22	86	22
		14	15	142	660	2	698	1
		18	49	55	79	23	465	5
		24	32	46	100	19	174	18
	Severely eroded	16	6	61	749	1	243	14
		19	22	72	230	12	340	11
Vertisols	Slightly eroded	6	0	0	0	25	0	25
	Moderately eroded	11	27	39	101	18	154	19
		17	28	123	311	8	409	7
	Severely eroded	21	4	28	528	3	100	21
Cambisols	Slightly eroded	2	2	7	217	13	31	23
		23	0	0	0	24	0	24
	Moderately eroded	10	25	37	103	17	224	17
		20	32	229	499	5	405	8
	Severely eroded	1	26	59	154	16	398	9
		5	20	76	260	9	255	13
Fluvisols	Slightly eroded	9	8	57	517	4	243	15
	Moderately eroded	22	20	28	98	20	159	20
Leptosols	Severely eroded	12	27	38	97	21	227	16
Planosols	Slightly eroded	15	27	92	233	10	557	2
	Moderately eroded	13	29	66	161	15	467	4
	Severely eroded	8	23	107	317	7	442	6
		25	34	160	333	6	346	10

Table 11.5 Ranking of the plots according to interrill erodibility values in rain 3

Soil characteristics			Erosion parameters		Kinnell model		Local model	
Soil types	Erosion classes	Plot	Runoff (mm)	Erosion (g/m^2)	$K_{iq}x10^{-4}$ ($kg\ s^{-1}\ m^{-4}$)	Rank (K_{iq})	$K_l x10^{-4}$ ($kg\ s^{-1}\ m^{-4}$)	Rank (K_l)
Lixisols	Slightly eroded	7	50	42	47	22	162	19
	Moderately eroded	3	40	40	56	20	81	23
		4	36	88	135	14	212	15
		14	59	226	213	8	434	6
		18	65	34	29	24	238	14
		24	69	156	125	15	268	12
	Severely eroded	16	32	329	571	2	489	3
		19	56	158	155	12	309	11
Vertisols	Slightly eroded	6	0	0	0	25	0	25
	Moderately eroded	11	50	48	53	21	99	22
		17	59	131	122	16	115	20
	Severely eroded	21	62	613	550	3	473	4
Cambisols	Slightly eroded	2	23	47	110	17	175	18
		23	7	33	255	6	66	24
	Moderately eroded	10	49	62	69	18	187	17
		20	68	710	580	1	505	1
	Severely eroded	1	44	157	197	11	423	7
		5	43	231	296	5	504	2
Fluvisols	Slightly eroded	9	23	82	197	10	253	13
	Moderately eroded	22	58	46	45	23	193	16
Leptosols	Severely eroded	12	46	48	58	19	103	21
Planosols	Slightly eroded	15	56	220	220	7	467	5
	Moderately eroded	13	65	179	152	13	417	8
	Severely eroded	8	42	153	203	9	412	9
		25	66	409	341	4	325	10

(1) Advantages of the local model

The ranking of the soils varies with the interrill soil erosion model considered, indicating differences in consistency with interrill soil erodibility. Contrary to the Kinnell model, the local model accounts for the integrated effect of runoff and soil loss when estimating the interrill soil erodibility. When different soils have a similar soil loss, soils with high runoff receive more weight than those with small runoff. In other words, interrill erodibility calculated from the local model represents both the susceptibility of the soil to erosion and the actual amount of runoff as measured on a unit plot. This behaviour agrees with the USDA-SWC (1993) definition of soil erodibility. For instance, plot 21 on severely eroded Vertisols and plot 22 on moderately eroded Fluvisols exhibited each a soil loss value of $28g/m^2$ in rain 2. Runoff amounts were 4 and 20 mm, respectively. The corresponding ranks with the local method were 21st (K_l = 100 x 10^{-4} kg s^{-1} m^{-4}) and 20th (K_l =159 x 10^{-4} kg s^{-1} m^{-4}), respectively. With the Kinnell model, the ranks were 3rd (K_{iq} = 528 x 10^{-4} kg s^{-1} m^{-4}) and 20th (K_{iq} = 98 x 10^{-4} kg s^{-1} m^{-4}), respectively (table 11.4). A substantial discrepancy between the ranks when using the Kinnell model suggests less accuracy of the model in estimating the interrill soil erodibility, because it does not account for runoff difference between soils (Truman and Bradford, 1995).

Another advantage is that the local interrill soil erosion model is more consistent with soil loss than the Kinnell model. For instance, soil loss values for plot 15 on slightly eroded Planosols, plot 9 on slightly eroded Fluvisols and plot 23 on slightly eroded Cambisols were 220, 82 and 33 g/m^2, respectively in rain 3. They occupied the ranks 5th ($K_l = 467 \times 10^{-4}$ kg s^{-1} m^{-4}), 13th ($K_l = 253 \times 10^{-4}$ kg s^{-1} m^{-4}) and 24th ($K_l = 66 \times 10^{-4}$ kg s^{-1} m^{-4}), respectively using the local model; whereas the ranks were 7th ($K_{iq} = 220 \times 10^{-4}$ kg s^{-1} m^{-4}) 10th ($K_{iq} = 197 \times 10^{-4}$ kg s^{-1} m^{-4}) and 6th ($K_{iq} = 255 \times 10^{-4}$ kg s^{-1} m^{-4}), respectively using the Kinnell model (table 11.5). This implies that the segregation between interrill soil erodibility classes using the local model is linear and discriminant, enhancing its consistency, whereas the interrill soil erodibility classes contrast with the interrill soil erosion parameters with the Kinnell model, illustrating poor consistency.

(b) Disadvantages of the local model

The local interrill soil erosion model is less consistent in the estimation of interrill soil erodibility for soils showing a considerable accumulation of coarse fragments on the soil surface and in the topsoil layer. For instance, in the rain 2 plot 24 on moderately eroded Lixisols exhibits higher values of soil loss (46 g) and runoff (32 mm) than plot 12 on severely eroded Leptosols where values of 38 g and 27 mm were recorded for soil loss and runoff amount, respectively. But the plot 12 occupies a higher rank (16th) than the plot 24 (18th). This ambiguity can be explained by the effect of the high concentration of coarse particles, that tends to increase the soil surface resistance. The coarse particle contents were 58% for plot 12 on severely eroded Leptosols and 22% for plot 24 on moderately eroded Lixisols. The soil surface resistance values were 1.7 and 0.9 Pa, respectively. The soil surface resistance was based on the fine soil particles located between the coarse particles. Because of a substantial concentration of coarse particles, the shear strength of the soil surface was overestimated, since the blades of the torvane closely located between rock particles produced high resistance values, reducing the precision in the computation of the interrill soil erodibility. This implies that, for soils showing a high coarse particle cover or a significant amount of rock fragments in the topsoil layer, adjustments must be made to account for the effect of the coarse particles.

11.3 ASSESSMENT AND CHARACTERIZATION OF THE MODEL

11.3.1 Model component evaluation

Apart from the interrill erodibility parameter, the local model of interrill erosion consists of three components, including rainfall amount, runoff amount and soil surface resistance. Each component strongly influences interrill soil loss.

(1) The influence of rainfall

During the investigations, it was observed that runoff on crusted soil surfaces started at the very early stage of rain, when rainfall intensity was still small. This implies that under certain soil surface conditions runoff can occur at very low rainfall intensities. Pontanier et al. (1984) report similar results. On some soils, such as moderately eroded Cambisols and severely eroded Vertisols, soil loss was substantial irrespective of the rainfall characteristics, indicating a high susceptibility of these soils to erosion. These results agree with works done by Lal in western Africa (1977), who found a rather low correlation between the maximum 30 minutes intensity (I_{30}) of a storm and soil loss. In the meantime, Roose (1975) reported a high correlation between rain erosivity and rainfall depth for a wide zone in the west Africa. So, rainfall amount has more weight than rainfall intensity in determining interrill erosion. This is rather obvious since rainfall amount integrates the two other rainfall characteristics, intensity and duration.

(2) The influence of runoff

On some soils, such as severely eroded Lixisols and severely eroded Vertisols, runoff started only at the advanced stage of the rain, when the topsoil layers were sufficiently wet or saturated. This indicates that, once the topsoil layer is saturated, peak erosion rates and peak runoff rates do not always coincide. On crusted soil surface, runoff increased with time, enhancing detachment by flow shear. Consequently, runoff amount has more weight than runoff rate in determining interrill erosion, because it integrates the two other runoff characteristics, intensity and duration.

(3) The influence of the soil surface resistance

Although it is obvious that interrill soil loss correlates positively with runoff, some soils, such as slightly and moderately eroded Lixisols, generate high amounts of runoff but accompanied with small soil loss. This difference in response is probably due to soil surface conditions, that resist to detachment by splash and flow. The integration of the parameter "soil surface resistance" in the interrill erosion model improves the estimation of interrill soil loss on resistant soil surfaces that generate high runoff.

In fact, the soil surface resistance appears to be a synthetic parameter, that integrates all the soil properties controlling cohesion and regulating structural stability of the soil surface aggregates. Implicitly, it translates particle size, structure, organic matter content, and aluminum and iron hydrous oxide contents. The critical level of the soil surface resistance can be considered as the smallest value of soil surface resistance that corresponds to the highest rates of soil loss. That level tends to be zero and is reached when the soil surface aggregates are saturated. A soil profile displays different horizons with distinct physical and chemical properties. This implies that truncation of the soil by erosion alters the properties of the topsoil layers and exposes the subsoil layers at the surface with different resistance. So, changes in the soil surface properties can be detected by the changes in the soil surface resistance, indicating changes in the erosion function as changes in the topsoil properties. Soil detachment by flow should be based on the critical hydraulic shear (Foster et al., 1977).

11.3.2 Main model characteristics

The interrill soil erosion equation represents individual sub-processes of interrill erosion, strengthening interactions among interrill erosion parameters due to changes in soil properties, rainfall and runoff characteristics during rain showers. As a consequence, the local interrill erosion model can be considered as a mathematical model, because the behaviour of the system is represented by a set of equations, together with logical statements expressing relationships between variables and parameters. Generally speaking, the local model of interrill erosion exhibits four main characteristics:

- The model is a physically-based and distributed model, because it can predict interrill soil loss where no data are available. It accounts for spatial and temporal variability of rainfall characteristics, soil properties and runoff characteristics.

- The model is based on the delineation and quantitative description of fundamental interrill sub-processes. It is expressed as functions of rainfall characteristics, runoff characteristics and soil surface resistance, to reflect the expected changes in soil loss during a rainfall event.

- The model is an event-based model, because it represents a single rainfall shower occurring over a period of time (rainfall duration). The effects of rainstorm characteristics on soil erosion can be investigated.

- The model is a hill-slope (or single-field) model, because it can operate at field scale, which is useful for designing erosion control measures at farm level.

11.4 CONCLUSION

The study of fundamental interrill soil erosion processes has provided basic, coherent and logical knowledge to develop a local model of interrill soil erosion, consisting of four variables: (1) the interrill soil erodibility; (2) the rainfall amount; (3) the runoff amount; and (4) the soil surface resistance. This model is more accurate than the Kinnell model for predicting soil loss. Therefore, the local model of interrill erosion is used in the following chapter for assessing interrill soil erodibility.

CHAPTER 12

INTERRILL SOIL ERODIBILTY

Interrill soil erodibility is derived and related to soil properties. It varies according to the erosion classes of the main soil types. Relative classes of interrill soil erodibility and erosion hazard are determined for each map unit.

12.1 VARIATION OF THE INTERRILL SOIL ERODIBILITY

12.1.1 Variations between rains

Interrill soil erodibility might increase, decrease or remain constant with increasing rainfall characteristics in terms of intensities, durations and number of events (table 12.1). Ten plots, representing 40% of the experimental sites, show an increase in interrill soil erodibility in rain 3. For instance, on severely eroded Vertisols, the values of interrill erodibility are 100 and 473 kg s^{-1} m^{-4}($x10^{-4}$) in rain 2 and rain 3, respectively. Similar behaviour is observed on severely eroded Cambisols.

Table 12.1 Values of interrill erodibility for erosion classes of major soil types

Soil types	**Erosion classes**	**Plot**	**Rain 2**	**Rain 3**
			$K_I x10^{-4}$ (kg s^{-1} m^{-4})	$K_I x10^{-4}$ (kg s^{-1} m^{-4})
Lixisols	Slightly eroded	7	312	162
	Moderately eroded	3	497	81
		4	86	212
		14	698	434
		18	465	238
		24	174	268
	Severely eroded	16	243	489
		19	340	309
Vertisols	Slightly eroded	6	0	0
	Moderately eroded	11	154	99
		17	409	115
	Severely eroded	21	100	473
Cambisols	Slightly eroded	2	31	175
		23	0	66
	Moderately eroded	10	224	187
		20	405	505
	Severely eroded	1	398	423
		5	255	504
Fluvisols	Slightly eroded	9	243	253
	Moderately eroded	22	159	193
Leptosols	Severely eroded	12	227	103
Planosols	Severely eroded	15	557	467
	Moderately eroded	13	467	417
	Severely eroded	8	442	412
		25	346	325

In contrast, eleven plots representing 44% of the experimental sites show a decrease in interrill soil erodibility, despite an increase in rainfall intensity and duration in rain 3. On slightly eroded Lixisols, the values of interrill erodibility are 312 and 162 kg s^{-1} $m^{-4}(x10^{-4})$ in rain 2 and rain 3, respectively. Similarly, slightly eroded Planosols and moderately eroded Vertisols exhibit a decrease of interrill erodibility between consecutive rains. Lastly, the interrill soil erodibility values remained similar between the rains on three plots (12%). For instance, slightly eroded Vertisols (plot 6) show no variation of the interrill soil erodibility value between the rains.

Interrill soil erodibility changes with time, reflecting changes in soil properties and soil surface conditions. For instance, decreased soil surface roughness, crust formation, saturation of the topsoil layers promote dispersion of the soil surface aggregates, decrease soil macroporosity and enhance runoff and erosion (Young et al., 1990). Temporal variability of the interrill soil erodibility suggests changes in ranking as well as magnitude of the resistance of soil to erosion (Bryan et al., 1989). Therefore, seasonal interrill erodibility values, that could reduce errors in soil loss estimates, are needed (Young et al., 1990).

12.1.2 Variations of interrill soil erodibility between soil types

The order of increasing relative interrill erodibility of the soil types changes according to erosion classes (figure 12.1). Considering only the results obtained in rain 3, the order is: (1) Vertisols < Cambisols < Lixisols < Fluvisols < Planosols on slightly eroded soils; (2) Vertisols < Fluvisols < Lixisols < Planosols < Cambisols on moderately eroded soils; and (3) Planosols < Cambisols < Vertisols < Lixisols on severely eroded soils.

(a) (b)

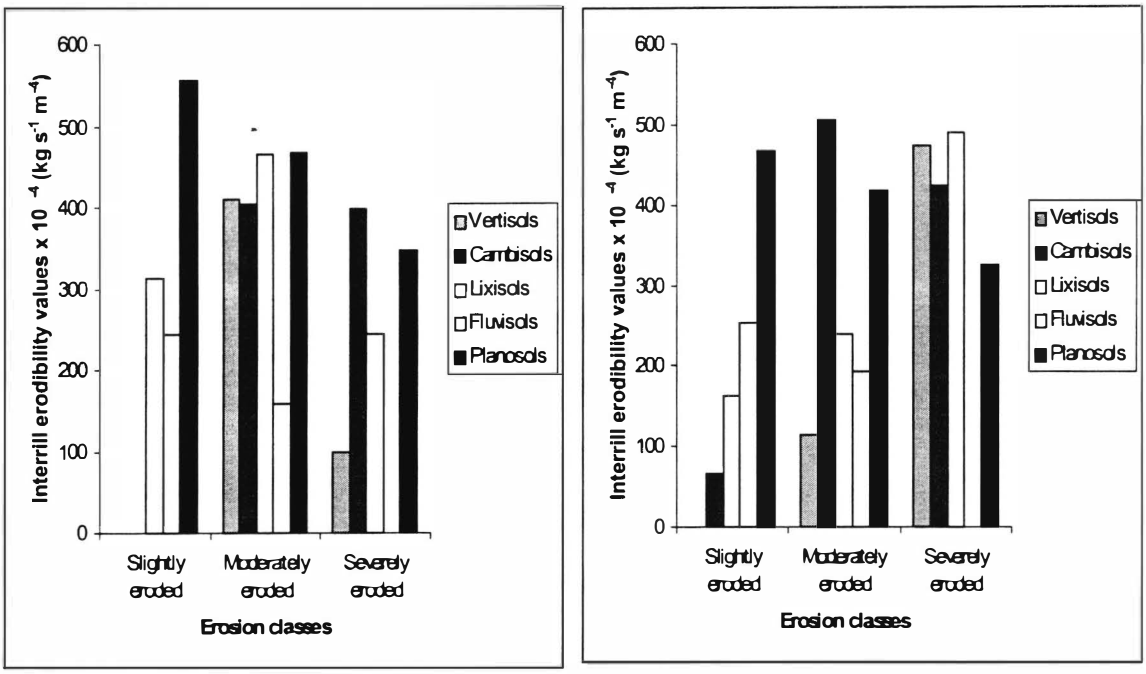


Figure 12.1 Variations of the interrill soil erodibility between erosion classes of the major soil types (a) in rain 2 and (b) in rain 3.

12.1.3 Variations between erosion classes

As expected, established erosion classes show differences in interrill soil erodibility. On Lixisols and Vertisols, the order of increasing interrill erodibility in the third rain is indicated by slightly eroded < moderately eroded < severely eroded. It is: severely eroded < moderately eroded < slightly eroded on Planosols. The general tendency is that soils already eroded show high interrill erodibility values. This may vary over considerable ranges. On Vertisols for example, a value of zero was observed on slightly eroded soils and a value of 472 kg s^{-1} m^{-4} ($x10^{-4}$) on severely eroded soils (figure 12.1).

12.2 DETERMINATION OF INTERRILL SOIL ERODIBILITY FROM SOIL PROPERTIES

To determine the relationships between interrill soil erodibility and soil properties, stepwise backward multiple regression analysis was applied to three data sets, including: (1) 50 values for each of the ten selected morphological and physical properties of the topsoil layer; (2) 50 values for each of the nine selected chemical properties of the topsoil layer; and (3) 50 values for each of the nineteen selected properties of the topsoil layer measured from each rainfall simulation plot. Data indicate that the relationships vary with soil properties.

12.2.1 The influence of morphological and physical properties

Soil properties, such as clay, coarse silt, sand and bulk density, exhibit positive relationships with interrill soil erodibility. Other soil properties, including fine silt, coarse fragments, depth to subsurface horizon, structure and antecedent soil moisture content, display negative correlation with interrill soil erodibility (table 12.2).

Table 12.2 Regression coefficients for morphological and physical soil properties

Variable	Coefficient	Variable	Coefficient
Constant	-1662	Coarse particles	-3.27
Clay	21.15	Bulk density	724.55
Fine silt	-5.66	Thickness of topsoil layer	-3.02
Coarse silt	15.76	Structure	-7.51
Fine sand	12.53	Antecedent soil moisture content	-0.87
Coarse sand	6.85		

(1) Positive relationships between soil properties and interrill soil erodibility

(a) The influence of clay

In discordance with Wischmeier and Mannering (1969), there is a positive correlation between the percentage of clay and interrill soil erodibility. This can be attributed to the chemical and physico-chemical forces interacting to bind clay particles and aggregates together.

Increased soil volume due to swelling is not always accompanied by water content increase. In general, swelling depends on clay type, saturation of the exchange complex and presence of soluble salts. Swelling increases with increasing clay content. The greater the clay content, the higher the plasticity, the greater the shrinkage-swell potential, the lower the hydraulic conductivity, and the higher the cohesion. The clay fraction has high void ratio and soil moisture storage. In clayey soils, the dominant interparticle force is the repulsion force determining the distances between clay particles. The higher the water content and void ratio of the soil, the greater the likelihood of disturbance due to changes in the microfabric resulting from the removal of the interlayer water, which reduces cohesion (Yong and Warkentin, 1975; Mitchell, 1993).

Swelling is due to repulsion resulting from diffuse ion-layer interpenetration, causing disintegration of aggregates, promoting dispersion and enhancing erosion. Moriwaki et al. (1982) and Seedsman (1986) identified four modes of desintegration:

- dispersion slaking: particles of clay detach from the surface of the intact clay by dispersion into the adjacent water;
- swelling slaking: water is adsorbed by the clay and the material swells and softens;
- surface slaking: aggregates of clay particles spall off the surface and accumulate as sediment in the adjacent water; and
- body slaking: the material splits and disintegrates into pieces, and the failure appears to develop from the inside out.

Despite a positive correlation between the clay content and soil surface aggregate cohesion, clay particles are more susceptible to transport after they have been detached by raindrop impact and by surface flow, because they are lighter. The ratio of clay-organic matter in the topsoil layer may considerably influence interrill erodibility. Soil surface aggregates containing a high clay percentage and a very small organic matter content (< 2%) are more susceptible to erosion in aggregated forms (Wishmeier and Mannering, 1969). Many soils of the Gawar area exhibit organic matter content less than 2%, confirming the above statement.

On Vertisols the dominant clay minerals are smectites (montmorillonite), whereas the type of clay mineral found in the other major soil types of the semiarid zone of Cameroon is kaolinite (Seiny, 1990; Mahop and Van Ranst, 1995). Montmorillonite has a high capacity to adsorb water, causing runoff and erosion to decrease. Kaolinite has the lowest water adsorption capacity of the common soil clay minerals due to its smaller interlayer space. This allows clay lamellae to adsorb only a small amount of water molecules, promoting deflocculation (dispersion), decreasing the structural stability and enhancing runoff and soil loss. For instance, at 50% relative humidity (at which the soil is dry), the mass of water adsorbed per mass of soil is 21% for montmorillonite and only 0.5% for kaolinite. This causes the water film thickness to range from a few molecular layers (about 8 Å for kaolinite) to many layers (up to 68 Å for montmorillonite) (Greenland and Hayes, 1978; Jury et al., 1991; White, 1997).

(b) The influence of coarse silt, fine sand and coarse sand

Positive relationships between interrill erodibility and soil particles, such as coarse silt, fine sand and coarse sand, can be explained by the cohesion between the particles. The binding forces acting between coarse soil particles are rather poor, enhancing detachment by raindrop impact and overland flow.

Sand and silt fractions reduce shrinkage, because they dilute the clay fraction and decrease the volume of water held by the soil. When water is added to a collapsing soil in which sand and silt grains are stabilized by clay particles, the effective strength in the clay is reduced. The clay swells, becomes weaker, and contacts fail in shear (Mitchell, 1993), which enhances erosion. In addition, the aggregate stability decreases and the susceptibility to formation of disruptional crusts increases with increasing coarse silt and sand contents. Coarse silt behaves as sand. Disruptional crusts promote runoff and soil loss (Bryan, 1974; Luk, 1977; Verhaegen, 1984).

(c) The influence of the bulk density

A positive correlation between bulk density and interrill soil erodibility reflects the influence of the soil properties that govern permeability and regulate percolation. Compaction and soil porosity vary inversely. But there is a positive relationship between bulk density and compaction, leading to a negative correlation between bulk density and porosity. A high bulk density due to compaction decreases soil porosity and infiltration rates and increases runoff and erosion.

(2) Negative relationships between soil properties and interrill soil erodibility

(a) The influence of fine silt

A decrease of interrill soil erodibility with increasing fine silt content can be explained by the effect of silt on the soil surface aggregate cohesion. The fine silt behaves as clay particles by strengthening cohesion and structural stability of the soil surface aggregates. Increased silt contents favour the formation of resistant crusts at the soil surface, protecting soil particles from detachment by raindrop impacts and surface flow.

(b) The influence of coarse particles

Increased coarse particle contents in the topsoil layers enhance macro-porosity, causing infiltration to increase, runoff and erosion to decrease. In addition, high concentrations of coarse particles at the soil surface act as mulch since they protect finer soil particles from raindrop impacts and washing (Meyer et al., 1972).

(c) The influence of the depth to the B horizon or hard rock

The horizon sequence of many soils includes coarse-textured and more permeable topsoil layers (Ap and A2) above heavy, hard, structureless and less permeable deeper layers (Bt and bedrock). When the wetting front reaches a less permeable layer, the infiltration rate decreases and water moves laterally and upward in the topsoil layer, causing saturation overland flow, promoting runoff, decreasing cohesion, deteriorating surface structure and structural stability and enhancing erosion (De Ploey, 1986). In general, permeability and runoff depend on the least permeable horizon in the layer sequence. When a soil layer of different texture and permeability from the surface layer is present in the soil profile, infiltration rates decrease, regardless of whether it is coarser or finer than the surface layer. Decrease in infiltration rates is attributed to the conditions of unsaturated conductivity as the wetting front reaches the interface (Jury et al., 1991).

The effective surface horizon depth is important for the water storage capacity. When all conditions regulating the permeability are the same, it is obvious that overland flow production is quicker and higher in a thin than in a thick topsoil layer. Decreased effective depth of the topsoil layer reduces water detention before surface runoff and subsequent erosion start.

(d) The influence of the structure

A structured topsoil layer enhances macro-porosity, causing infiltration to increase due to water percolation, which reduces runoff and decreases erosion.

(e) The influence of antecedent soil moisture content

In contrast to Barnett and Rogers (1966), Lyles et al. (1974) and Kamper et al. (1985), there is a negative correlation between interrill soil erodibility and antecedent soil moisture content. The difference in response can be attributed to the ambivalent effect of resistant crust layers. Resistant crusts form after some water has penetrated into the soil and part of it is retained as soil moisture. After the crust layers are formed, infiltration decreases while runoff increases, but soil detachment decreases. After the rain, the crust layers protect soil moisture beneath from evaporation (Truman and Bradford, 1990; Truman et al., 1990).

(3) Modelling interrill soil erodibility from significant morphological and physical soil properties

From ten morphological and physical soil properties, the best subset of interrill erosion predictors with R^2 value of 0.227 and P-value of 0.019 consists of four variables, including (1) bulk density, (2) clay content, (3) structure, and (4) coarse particle content, as expressed in the following equation:

$$K_I = -512.61 + 533.49*Db + 8.77*Cl - 5.5*St - 3.01*Cp$$

where K_I is interrill soil erodibility in kg s^{-1} m^{-4}; Db is bulk density in Mg m^{-3}; Cl is clay content in %; St is simplified structure code (10 to 43); and Cp is coarse particle content in %.

In the model, bulk density is positively related to interrill erodibility and ranks higher among the selected parameters, indicating that most of the important transport and retention processes in the soil are strongly influenced by properties controlling bulk density. These properties are commonly characterized by individual soil particles, void space (porosity) and water film (Jury et al., 1991). In fact, soil bulk density appears to be a synthetic parameter, that integrates all the soil properties that control permeability and regulate percolation. Implicitly, it is relevant to porosity, structure, texture, compaction and water holding capacity. Bulk density is inversely related to total porosity and water holding capacity. Porosity depends on the relative particle size distribution and particle arrangement. During compaction soil aggregates are destroyed, reducing soil porosity. Compaction results in reduced porosity and so can be detected from an increase in bulk density. Bulk density can be considered as an index of structure and porosity (Koolen and Kuipers, 1983). The structure and coarse particles create physical conditions for adequate porosity controlling the state and the circulation of water, adequate water holding capacity, resistance of the soil to slaking and sealing, and low compaction. In saturated soils, the flow rate is high in coarse-textured soils where aggregates, channels and cracks are present (Wild, 1995), causing runoff and soil loss to decrease.

12.2.2 The influence of chemical soil properties

Soil properties such as nitrogen, potassium and pH water exhibit positive relationships with interrill erodibility. Other soil properties, including organic matter content, phosphorus, free iron, calcium, magnesium and sodium display negative correlation with interrill erodibility (table 12.3).

Table 12.3 Regression coefficients for selected chemical soil properties

Variable	Coefficient	Variable	Coefficient
Constant	233.63	Calcium	-10.61
Organic matter	-286.2	Magnesium	-1.53
Nitrogen	5120.9	Potassium	43.21
Phosphorus	-7.38	Sodium	-35.48
Free iron	-22.87	pH water	34.10

(1) Positive relationships between soil properties and interrill soil erodibility

(a) The influence of potassium

Positive relationships between potassium and interrill erodibility can be attributed to the low ionic potential of potassium, causing water-repellence to a certain extent. When potassium ions are dominant in the soil, repulsive forces prevail between clay particles and the swelling pressure forces cause the clay layers to apart from one another. The particles move farther apart to exist as separate entities, enhancing deflocculation (dispersion) and decreasing aggregate stability (Wild, 1995).

(b) The influence of pH

The interactions between pH and clay play an important role in clay suspension. A low pH promotes a positive edge to negative surface interaction, often leading to flocculation from suspension. Dispersion of clay particles requires high pH conditions. Dispersive state of clay promotes erosion (Yong and Warkentin, 1975; Mitchell, 1993). Wischmeier and Mannering (1969) found positive relationships between interrill erodibility and pH and attributed this behaviour to the silt content.

(c) The influence of nitrogen

Nitrification is an essential step to nitrogen losses by NO_3^- reduction and the evolution of N_2O and N_2. The process requires biological activity of microorganisms (nitrosomonas and nitrobacter). Carbon-nitrogen ratio (C/N) influences the trend of the process. When C/N is greater than 25 (the amount of nitrogen is small), immobilization occurs. But when it is less than 25 (the amount of nitrogen is high), mineralization occurs. An intensive mineralization process causes a decrease in soil organic matter contents. Optimal nitrification conditions require optimum temperature (30-35°C), optimum moisture content (60% of field capacity) and optimum pH (6.6) (Wild, 1995).

(2) Negative relationships between soil properties and interrill soil erodibility

(a) The influence of the organic matter content

Negative relationship between organic matter content and interrill erodibility can be attributed to the binding action of the organic matter. Soil organic matter holds soil particles together and enhances the resistance of the soil surface aggregates to dispersion and detachment by raindrops and surface flow. Soil organic matter has a high water-holding capacity, causing infiltration to increase, and runoff and erosion to decrease.

(b) The influence of phosphorus

The main source of phosphorus is dust deposits, particularly during dry seasons. Soil phosphorus may exist in strongly adsorbed or insoluble forms, or as organic phosphorus which is the major source of phosphorus for the soil micro-organisms and mesofauna. Increased soil phosphorus contents cause an increase of the soil fauna population and soil organic matter contents (Wild, 1995), leading soil cohesion to increase, macro-porosity to increase, infiltration to increase, and runoff and soil loss to decrease.

(c) The influence of free iron and sodium

Increased aluminium and iron hydrous oxides enhance aggregate stability due to cementing effects between soil particles (Roth et al., 1974). In the clay fraction, the dominant interparticle force is that of repulsion, causing swelling. Swelling increases with decreasing valence of the exchangeable basic cations. A substitution of divalent for monovalent exchangeable basic cations, such as sodium, reduces the repulsion, causing the liquid limit to decrease. A decrease in repulsion may be accompanied with increased flocculation (Yong and Warkentin, 1975), leading erosion to decrease.

(d) The influence of calcium and magnesium

High ionic potentials for calcium and magnesium create hydrophilic condition. When calcium and magnesium ions are dominant in the soil, attractive forces prevail, causing clay particles to remain close together (Wild, 1995), which enhances flocculation and increases aggregate stability.

(3) Modelling Interrill soil erodibility from significant chemical soil properties

From nine chemical soil properties in total, the best subset of interrill erosion predictors with R^2 value of 0.354 and P-value of 0 consists of three variables, including (1) organic matter content, (2) calcium content, and (3) phosphorus content as expressed in the following equation:

$$K_I = 532.64 - 163.7*OM - 7.66*Ca - 5.06*P_2O_5$$

where K_L is interrill erodibility (kg s^{-1} m^{-4}), OM is organic matter content (%), Ca is calcium content (cmol(+) kg^{-1} of soil), and P_2O_5 is phosphorus content (cmol(+) kg^{-1} of soil) readily available to plants.

All the independent variables of the model are inversely related to interrill erodibility. As expected, organic matter content ranks highest among the selected variables, highlighting its influence on the other soil properties as described by Koolen and Kuipers (1983) and Wild (1995).

- As binding agent between soil particles, organic matter strengthens the aggregation of the soil particles and the stability of the aggregates. It contributes to the retention of cations, as well as to the pH buffering properties of soils. The plant nutrients, such as nitrogen, phosphorus and sulfur are contained in organic compounds. When the organic compounds are mineralized by the action of micro-organisms, these three elements are released as inorganic ions and may then be taken up by plants. Fungal hyphae and fine roots bind together aggregates larger than 2 mm. Medium-sized aggregates are more stable because of the binding action by humus.

- Organic matter interacts with clay minerals and oxides of iron and aluminium to form stable soil aggregates, thereby improving the soil physical conditions to resist erosion. It acts as a sink for rain water due to a high water-holding capacity, reducing runoff and erosion.

- Under wet conditions, soils with a high content of organic matter are more resistant to compaction than soils with low organic matter content. Soil compaction reduces soil porosity and enhances runoff and soil loss.

- Phosphorus contents and organic matter contents correlate positively.

In general, there are several sources of soil cohesion. Yong and Warkentin (1975) and Mitchell (1993) identified five main forces describing attraction between soil particles: (1) cohesive strengths resulting from cementation by chemical bonding between soil particles; (2) apparent attraction between soil particles due to capillary stresses; (3) electrostatic and electromagnetic attractions; (4) primary valence bonding and adhesion; and (5) mechanical forces due to packing and interlocking. Among these forces, the most important one is the holding of soil particles through bonds by cementing agents, including organic matter, calcium and phosphorus. Increased cementing agent contents lead to a high plasticity index, high shrinkage and high cohesion, causing runoff and erosion to decrease. Small amounts of cementing agents may have high effects on the stability of a soil. For instance, increasing the carbon content by only 1 or 2% may increase the plastic index by as much as an increase of 10 to 20% in the amount of clay. On disturbance, the cemented bonds are destroyed, leading to reduced strength (Mitchell, 1993).

12.2.3 Best subset predictors from all selected soil properties

The best interrill erosion predictors including morphological, physical and chemical soil properties with R^2 value of 0.669 and P-value of zero consist of thirteen variables (table 12.4).

Table 12.4 Regression coefficients for the best sub-set derived from all soil properties

Variable	Coefficient	Variable	Coefficient
Constant	-916.2	Organic matter content	-318.16
Nitrogen	3985.048	Magnesium	-24.339
Bulk density	815.275	Fine silt	-24.216
pH water	129.424	Coarse sand	-9.977
Sodium	18.868	Fine sand	-9.132
Coarse particles	3.217	Phosphorus	-12.505
Thickness of topsoil layer	2.758	Structure	-5.367

Some soil properties, such as coarse particles, coarse sand, fine sand and thickness of the topsoil layer, exhibit an ambivalent effect. In addition, certain soil properties such as clay and calcium do not appear as predictors, when all the properties are analyzed in the same data set. This highlights the relevance of using separate models for morphological and physical properties and for chemical properties, respectively. In general, the use of individual interrill erodibility models provides the following advantages:

- small number of predictors in each model, which permits better data handling;
- avoidance of the ambivalence of certain soil properties;
- avoidance of the exclusion of significant soil properties.

In general, the determination of interrill erodibility levels on the field will consist of the examination of the variables involved in the interrill erodibility equation derived from morphological and physical soil properties. The equation determined from chemical soil properties is suitable for the study in the laboratory. The segregation between the two models enhances the complementarity of the models and strengthens the investigations on soil erodibility as a whole. More eroded soils show better chemical status than less eroded soils. In addition, their topsoil layers show higher organic matter contents due to animal excreta. But less eroded soils have better morphological and physical status than more eroded ones. Using the interrill erodibility equations separately and combining the different results may lead to a better assessment of the interrill erodibility parameters in the study area.

12.3 INTERRILL SOIL ERODIBILITY AND EROSION HAZARD CLASSES

12.3.1 Determination of interrill soil erodibility classes

The values of interrill erodibility obtained in rain 3 on each experimental plot were used to determine the interrill soil erodibility classes. Two main reasons dictated the choice of the third rain results to establish comparisons between soil classes and between erosion classes. The first reason is that most soils showed substantial increase of interrill erodibility with time, so that average values of interrill erodibility may hide the steps of the erosion process. The second reason is that the third rain reflected dominant conditions found in the field, whereas the second rain translated only a transitory situation. At an earlier stage of the rainfall, the differential behaviour of the erosion parameters due to soil differences is hidden by the effect of the initial soil surface roughness created by ploughing.

A graph representing the rank of each experimental plot on the x-axis and the corresponding erodibility value on the y-axis was plotted (figure 12.2). The boundary between two consecutive classes of interrill soil erodibility was placed at the point where a slope break in the erodibility curve occurred, indicating a substantial discrepancy of interrill erodibility between soils with adjacent ranks. This allowed to identify three classes of relative interrill soil erodibility, including (1) very low to low relative interrill erodibility class; (2) medium relative interrill erodibility class; and (3) high to very high relative interrill erodibility class. The characteristics of these classes are presented in tables 12.5 to 12.7.

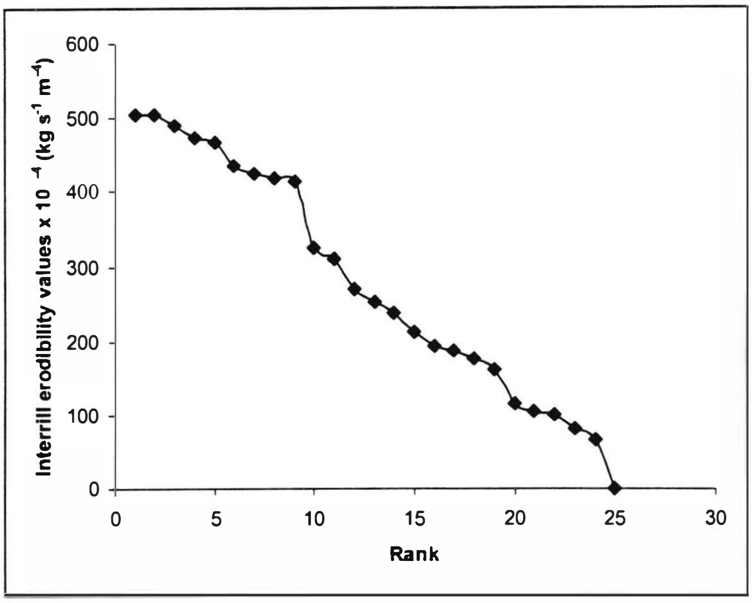


Figure 12.2 Ranking of the experimental plots according to interrill erodibility.

Table 12.5 Relative classes of interrill soil erodibility

Soil types	Erosion classes	K_I x 10^{-4} (kg s^{-1} m^{-4})	Interrill soil erodibility classes
Lixisols	Severely eroded	300 to 505	High to very high
Vertisols	Severely eroded		
Cambisols	Moderately eroded Severely eroded		
Planosols	Slightly eroded Moderately eroded Severely eroded		
Lixisols	Slightly eroded Moderately eroded	80 to 268	Medium
Vertisols	Moderately eroded		
Cambisols	Slightly eroded		
Fluvisols	Slightly eroded Moderately eroded		
Leptosols	Severely eroded		
Vertisols	Slightly eroded	0 to 66	Very low to low
Cambisols	Slightly eroded		

Table 12.6 Erodibility classes and major morphological and physical soil properties

Interrill soil erodibility classes	K_I x10^{-4} (kg s^{-1} m^{-4})	Bulk density (Mg m^{-3})	Clay (%)	Coarse particles (%)	Structure
High to very high	300 - 505	1.5 - 1.7	5 - 30	6 - 43	Fine prismatic, subangular blocky, massive
Medium	80 - 268	1.4 - 1.6	5 - 29	0 - 36	Fine prismatic, subangular blocky, massive
Low to very low	0 - 66	1.3 - 1.4	29 - 31	7 - 38	Coarse prismatic

Table 12.7 Erodibility classes and major chemical soil properties

Interrill soil erodibility classes	K_L x10^{-4} (kg s^{-1} m^{-4})	Organic matter (%)	Calcium (cmol (+) kg^{-1})	Phosphorus (cmol (+) kg^{-1})
High to very high	300 - 505	0.1 – 1.72	2 – 16.32	1 – 45
Medium	80 - 268	0.7 – 1.43	1 – 15.48	2 – 43
Low to very low	0 - 66	0.8 – 1.72	2 – 16.46	3 – 22

Interrill erodibility increases with increasing erosion severity, indicating that the deterioration of the soil properties by past erosion exposes new soil conditions to severe erosion. For instance, classes of slightly, moderately and severely eroded Vertisols show very low to low, medium, and high to very high interrill erodibility, respectively. Cambisols exhibit similar behaviour. No erosion class of the Alfisols displays very low to low interrill erodibility, whereas all erosion classes of the Planosols show high to very high interrill erodibility and requires particular attention for soil and water conservation strategies, because they may cause substantial on-site as well as off-site erosion effects.

12.3.2 Determination of erosion hazard classes

The Gawar area was divided into interrill soil erodibility and slope gradient classes. The erosion hazard rate of each map unit was determined by summing the interrill soil erodibility rating with the slope gradient rating. The ranking method used allowed to determine three erosion hazard classes: (1) low erosion hazard class; (2) medium erosion hazard class; and (3) high erosion hazard class (tables 12.8 and 12.9).

Table 12.8 Erosion hazard for each erosion class of the major soil types

Soil types	**Erosion class**	**Slope gradient**		**Interrill soil erodibility**		**Erosion hazard**	
		Class	**Rate**	**Class**	**Rate**	**Rate**	**Class**
Lixisols	Slight	Level to nearly level	1	Medium	2	3	Low
Vertisols	Slight	Level to nearly level	1	Very low to low	1	2	
Cambisols	Slight	Level to nearly level	1	Very low to low	1	2	
Fluvisols	Slight	Level to nearly level	1	Medium	2	3	
	Moderate	Level to nearly level	1	Medium	2	3	
Lixisols	Moderate	Undulating	2	Medium	2	4	Medium
	Severe	Undulating	2	High to very high	3	5	
Vertisols	Moderate	Undulating	2	Medium	2	4	
	Severe	Undulating	2	High to very high	3	5	
Cambisols	Slight	Rolling	3	Medium	2	5	
	Moderate	Undulating	2	High to very high	3	5	
Leptosols	Severe	Rolling	3	Medium	2	5	
Planosols	Slight	Level to nearly level	1	High to very high	3	4	
	Severe	Undulating	2	High to very high	3	5	
Cambisols	Slight	Hilly to very steep	4	Medium	2	6	High
	Severe	Hilly to very steep	4	High to very high	3	7	
Leptosols	Severe	Hilly to very steep	4	High to very high	3	7	
Planosols	Moderate	Rolling	3	High to very high	3	6	

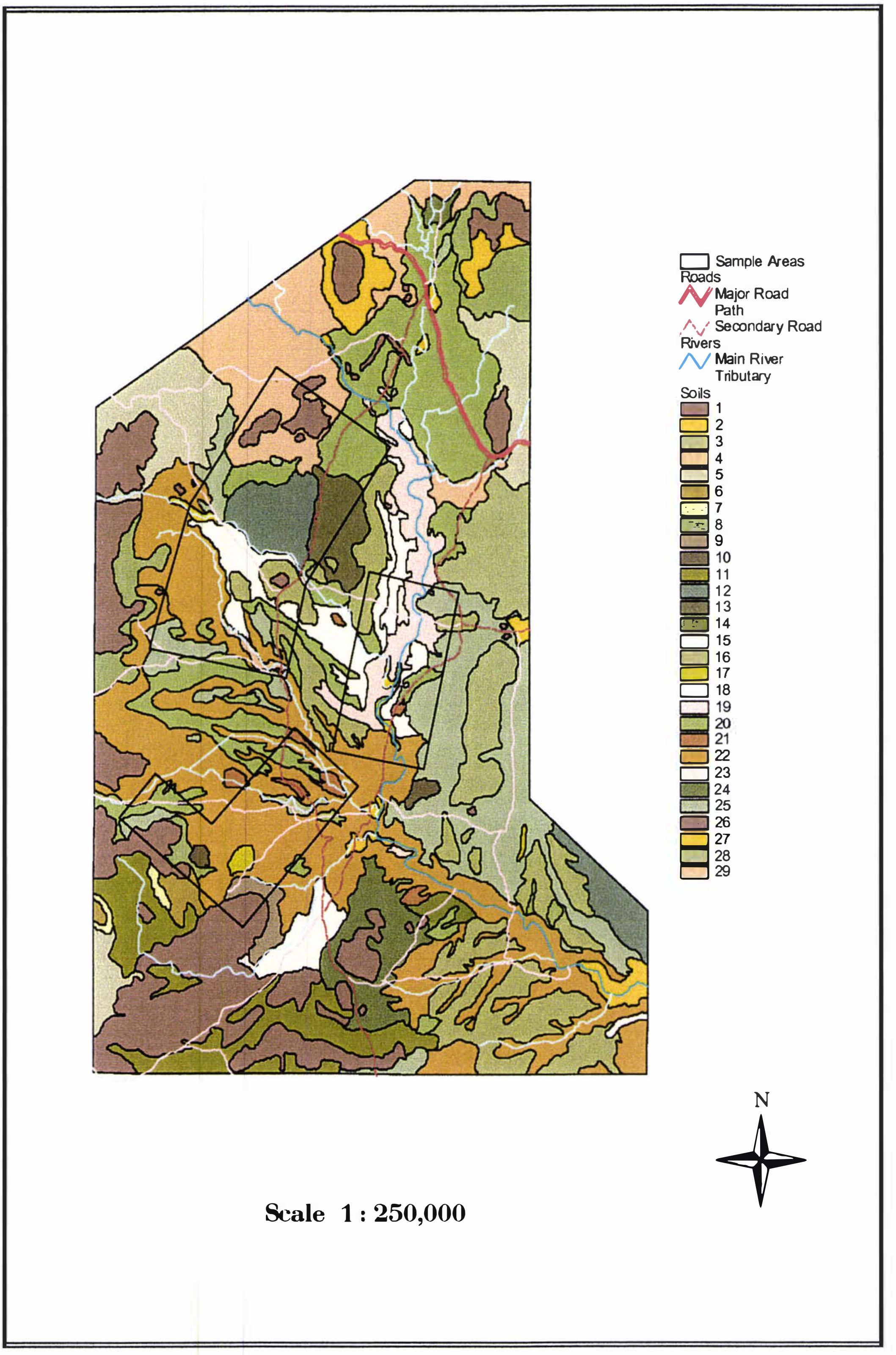


Figure 12.3 Soil erosion hazard map of the Gawar area

Table 12.9 Legend of the soil erosion hazard map (figure 12.3)

Landscape	Relief/Molding	Altitude (m)	Lithology	Landform	Map unit type	Slope (%)	Soil types (FAO, 1998)	Slope class	Interrill soil erodibility	Erosion hazard	Erosion status	Area (ha)	MU
Mountain	Ridges	700 - 1060	Granite, migmatite, anatexite, quartzite, basalt	Slope-facet complex	Association	15 - 60	Lithic Leptosols (*)	Hilly to very steep	High to very high	High	Excessive	10230	1
				Footslope	Consociation	12 - 20	Eutric Cambisols	Hilly to very steep	Moderate	High	Slight	1215	2
Hilland	Ridges	700 - 965	Granite	Slope-facet complex	Association	33 - 43	Lithic Leptosols (*)	Hilly to very steep	High to very high	High	Excessive	3345	3
Plateau	Hills in "half-orange"	700 - 900	Granite, migmatite, anatexite	Slope-facet complex	Association	8 - 9	Eutric Cambisols Lithic Leptosols	Rolling	Moderate	Moderate	Slight	5620	4
					Association	19 - 23	Lithic Leptosols (*)	Rolling	High to very high	High	Severe	3659	5
	Mesas	800 - 850	Gneiss, embrechite	Tread	Consociation	0 - 1	Haplic Lixisols	Level to nearly level	Moderate	Low	Slight	386	6
	Escarpments	600 - 800	Gneiss, embrechite (pediment)	Scarp-talus complex		24 - 40	Eutric Cambisols Lithic Leptosols	Hilly to very steep	High to very high	High	Severe	182	7
Piedmont	High glacis	580 - 600	Colluvium	Erosional glacis	Consociation	11 - 15	Lithic Leptosols	Rolling	Moderate	Moderate	Severe	2261	8
	Low glacis	560 - 580	Colluvium	Erosional glacis	Consociation	5 - 8	Haplic Lixisols	Undulating	Moderate	Moderate	Moderate	458	9
	Hills	700 - 900	Granite, anatexite	Slope-facet complex	Association	20 - 40	Lithic Leptosols (*)	Hilly to very steep	High to very high	High	Excessive	212	10
Peneplain	Hills in "Half-oranges"	600 - 650	Granite, migmatite, anatexite, gneiss	Slope-facet complex	Association	4 - 6	Haplic Lixisols Vertic Cambisols	Undulating	Moderate	Moderate	Moderate	3871	11
				Slope-facet complex	Association	4 - 8	Lithic Leptosols Haplic Cambisols	Undulating	Moderate	Moderate	Severe	2256	12

(*): Rock outcrops

Table 12.9 (continuation)

Landscape	Relief/Molding	Altitude (m)	Lithology	Landform	Map unit type	Slope (%)	Soil types (FAO, 1998)	Slope class	Interrill soil erodibility	Erosion hazard	Erosion status	Area (ha)	MU
Plain	High erosion glacis	590 - 605	Migmatite, quartzite	Tread-riser complex	Consociation	2 - 6	Haplic Lixisols	Undulating	Moderate	Moderate	Moderate	1186	13
					Association	3 - 8	Vertic Cambisols Chromic Lixisols Haplic Planosols	Undulating	High to very high	Moderate	Severe	299	14
	Middle erosion glacis	560 - 590	Gneiss, quartzite	Tread	Consociation	0 - 1	Haplic Lixisols	Level to nearly level	Moderate	Low	Slight	1919	15
			Embrechite	Tread	Consociation	0 - 1	Eutric Vertisols	Level to nearly level	Low to very low	Low	Slight	6949	16
				Riser	Consociation	1 - 2	Vertic Cambisols	Level to nearly level	Low to very low	Low	Slight	132	17
	Low erosion glacis	510 - 560	Gneiss, quartzite	Tread	Consociation	2 - 4	Haplic Lixisols	Undulating	Moderate	Moderate	Moderate	1825	18
				Riser	Consociation	2 - 6	Chromic Lixisols	Undulating	High to very high	Moderate	Severe	2345	19
			Embrechite	Tread	Consociation	2 - 4	Haplic Vertisols	Undulating	Moderate	Moderate	Moderate	10260	20
				Riser	Consociation	3 - 5	Haplic Vertisols	Undulating	High to very high	Moderate	Severe	460	21
					Consociation	3 - 10	Vertic Cambisols	Undulating	High to very high	Moderate	Moderate	16569	22
			Gneiss, migmatite	Tread	Consociation	2 - 3	Haplic Planosols	Level to nearly level	High to very high	Moderate	Slight	74	23
				Riser	Consociation	2 - 13	Haplic Planosols	Rolling	High to very high	High	Moderate	2071	24
					Consociation	2 - 5	Haplic Planosols	Undulating	High to very high	Moderate	Severe	7851	25
	Inselberg	600 - 800	Granite, quarzite, basalt	Slope-facet complex	Association	40 - 60	Lithic Leptosols (*)	Hilly to very steep	High to very high	High	Excessive	418	26
Valley	Floodplain	510 - 580	Recent alluvium	Tread	Consociation	0 - 1	Haplic Fluvisols	Level to nearly level	Moderate	Low	Slight	1147	27
					Consociation	0 - 1	Haplic Fluvisols	Level to nearly level	Moderate	Low	Moderate	144	28
	Terrace	550 - 580	Ancient alluvium	Tread	Consociation	3 - 4	Fluvic Cambisols	Undulating	Moderate	Moderate	Moderate	579	29

(*): Rock outcrops

Soils showing low erosion hazard are slightly eroded, suggesting that protection and preservation measures against erosion must be applied to ensure the sustainability of the productive capacity of these less eroded soils. Soils showing medium erosion hazard exhibit a high susceptibility to interrill erosion and are substantially eroded, requiring corrective, conservative as well as restorative measures to curb soil erosion and fertility depletion. Soils belonging to the high erosion hazard class are considerably eroded, exhibit high to very high susceptibility to erosion, and occupy unstable agricultural ecosystems (highlands). This implies that measures aiming at restoring the productive capacity of the soils, rehabilitating or preserving the ecosystems, must be envisaged. In general, the erosion severity increases with increasing erosion hazard. In contrast, a high erosion hazard associated with slightly eroded Cambisols is found on highlands where stone wall terraces are constructed and the soil fertility is maintained by mulch, animal manure and household waste uses. This is evidence that the stone wall terraces reduce the erosion potential to small levels, allowing sustainable crop production on unstable ecosystems.

12.4 CONCLUSION

The local interrill soil erosion model enabled clear insight as to the relationships between soil properties and interrill soil erosion. Morphological and physical topsoil properties, such as structure, bulk density, clay and coarse particle contents, and chemical properties, including organic matter, calcium and phosphorus contents were the best interrill erodibility predictors, indicating that topsoil properties controlling water movement and cohesion between soil particles play a major role in interrill erosion. Drastic variations of the interrill erodibility were observed between rains, soil types as well as between erosion classes within a given soil type, suggesting that the changes of soil properties due to erosion should deserve more attention. Extreme values of susceptibility to interrill erosion were obtained on different erosion classes of Vertisols and Cambisols.

CHAPTER 13

LAND USE OPTIONS FOR CONSERVATION PLANNING

While keeping the cultural practice heritage that has proved to be successful in soil conservation, suggested land use options as well as related farming systems are provided to help farmers to adapt to new circumstances for the development of agriculture and livestock. These strategies integrate crops, livestock, fodder and fuelwood to promote land use diversity and sustainable productivity in the Gawar area.

13.1 LAND USE OPTION PRINCIPLES

It is not recommendable to transfer to the Gawar area the technologies and systems that have been developed and found successful for agriculture in developed countries, since many of these technologies and systems have failed dramatically on small farms, where the hoe and manual labour prevail. It is not advocated either to return to the past farming systems or maintain the existing traditional subsistence farming systems, since they cannot cope with the food requirements caused by increased human and livestock populations. The current situation can be transformed into a more acceptable future by organizing and distributing the scarce natural resources among multiple objectives, that minimize costs and maximize benefits under a dynamic environmental and socio-cultural equilibrium.

Based on field observations and literature review, the study proposes to strengthen the actual integrated crop and livestock farming systems, selecting areas and production patterns suitable for annual crops, pastures and trees. Physically defined units, with known erosion status, were used for the development of soil conservation planning and sustainable productivity. Three land use options were identified: (1) the preservation and protection land use option; (2) the conservation and correction land use option; and (3) the rehabilitation and restoration land use option (table 13.1).

Table 13.1 Suggested land use options and farming systems for conservation planning

Land use options	Farming systems	Soils/landscapes
Preservation-Protection	Intensive terrace farming, stall feeding livestock	Highlands
	Intensive rainfed agriculture, stall feeding livestock	Slightly eroded Lixisols Slightly eroded Planosols Slightly eroded Cambisols Slightly eroded Leptosols Moderately eroded Vertisols
	Intensive post-rainy season cultivation, semi-extensive livestock	Slightly eroded Vertisols Slightly eroded Cambisols (vertic)
	Intensive irrigated agriculture, extensive livestock	Slightly and moderately eroded Fluvisols
Conservation-Correction	Integrated agro-sylvo-pastoral farming	Moderately eroded Lixisols Moderately eroded Planosols Moderately eroded Cambisols Moderately eroded Leptosols
Rehabilitation-Restoration	Intensive rainfed agriculture, stall feeding livestock	Severely eroded Vertisols
	Integrated sylvo-pastoral farming	Severely eroded Lixisols Severely eroded Planosols
	Nature preserves and leisure areas	Severely eroded Leptosols (highlands)

13.2 PRESERVATION AND PROTECTION LAND USE OPTION

The preservation and protection land use option emphasizes the management of slightly eroded soils. In fact, slightly eroded soils have high potential for crop production; they require land uses and protective measures against soil erosion to ensure a sustainable future for soil resources. Sustainable land use includes the systems that provide adequate ground cover during the cropping season, maintain soil fertility and conserve soil and water. To promote the conservation and rational utilization of slightly eroded soils, four types of farming system are suggested: (1) intensive terrace farming associated with stall feeding livestock; (2) intensive rainfed agriculture associated with stall feeding livestock; (3) intensive cultivation of post-rainy season Mouskwari sorghum associated with semi-extensive livestock; and (4) intensive irrigated agriculture associated with extensive livestock.

13.2.1 Intensive terrace farming associated with stall feeding livestock

The intensive terrace farming associated with stall feeding livestock is already practiced in some places of the Gawar area and has proved to be very effective in soil and water conservation. It is a system in which intensive measures for soil and water management are applied to restore and maintain soil fertility on steep highland slopes. Physical measures consist of stone wall terraces constructed along the contours.

Biological measures include mixed cropping and mulching. Soil fertility is maintained by the use of the animal manure and household refuses.

The livestock consists of raising small stocks around the house compounds, using stall feeding methods. Stall feeding is the practice of cut-and-carry fodder (crop residues) from the cultivated areas for animals, which prevents the stone wall terraces from damage due to animal movement. It also prevents the topsoil layer from pulverization and the subsoil layers from compaction, which decreases erosion. However, the animals may graze in the fallow fields and uncultivated areas.

13.2.2 Intensive rainfed agriculture associated with stall feeding livestock

The intensive rainfed agriculture associated with stall feeding livestock is an improved farming system to be practised on slightly eroded Lixisols, slightly eroded Planosols, slightly eroded Cambisols and moderately eroded Vertisols. It intends to replace the existing intensive rainfed agriculture associated with extensive livestock. The main advantage of this improved farming system is controlled soil loss.

Physical measures of runoff and erosion control consist of the ridge-furrow system done obliquely to the direction of the slope. The obliqueness of the erosion control structure is useful to reduce runoff velocity and avoid the accumulation of runoff, that may cause the ridge-furrow system to collapse when the threshold water storage is reached. Minimum tillage operations, including good management of plant residues and reduced soil disturbance, are also recommended.

Biological measures of runoff and erosion control include mixed cropping and crop rotation. The ridge-furrow system must be used with economically useful plants, that have a quick growing and extensive plant cover close to the ground surface. Because total denudation occurs during seedbed preparation, mulching at the soil/air interface is recommended to reduce raindrop impacts, decrease surface crusting, improve infiltration and reduce runoff and soil loss. Soil fertility should be improved by the use of the plant and animal manure. Also, nitrogen fertilizers must be used to stimulate early crop growth and provide large ground cover.

Excessive movement of cattle in the cultivated areas pulverizes the topsoil layer, compacts the subsoil layers and enhances erosion. Judicious livestock management such as stall feeding must be adopted. Stall feeding livestock entails improvement of the corrals to increase manure production and fencing pastures for rational grazing.

13.2.3 Intensive post-rainy season cultivation of Mouskwari sorghum associated with semi-extensive livestock

The intensive post-rainy season cultivation of Mouskwari sorghum associated with semi-extensive livestock is an improved farming system, that can replace the existing intensive post-rainy season cultivation of Mouskwari sorghum associated with extensive livestock on slightly eroded Vertisols. Extensive cattle movement during the dry season leaves soil particles exposed to the running water. The usefulness of the suggested system lies in three main advantages: (1) soil and water conservation; (2) increased Mouskwari sorghum production; and (3) increased fodder production.

(1) Soil and water conservation

Soil and water conservation measures include the practice of the broadbed system, that retains and absorbs heavy runoff, which reduces soil loss. This practice is applied in the surrounding areas and has proved to be effective in soil and water conservation.

(2) Increased Mouskwari sorghum production

The practice of the broadbed system promotes soil water storage during the rainy season, which ensures a good establishment of the plants and a high grain yield during the post-rainy season cultivation. Crop residues and grain yields are positively correlated.

(3) Increased fodder production

Slightly eroded Vertisols lie fallow during the rainy season. As a consequence, the fields can be managed to provide forage for cattle. For instance, seeds of grass and legume pastures can be sown at the early stage of the rainy season to provide fodder for the animals.

The semi-extensive livestock management means that the animals can graze on slightly eroded Vertisols only during the rainy season when the fields lie fallow.

Grazing on crop residues during the dry season must be prohibited, because cattle movement produces fine soil particles that fill up the cracks, reduce infiltration, and enhance runoff and soil loss.

13.2.4 Intensive irrigated agriculture associated with extensive livestock

Intensive irrigated agriculture associated with extensive livestock already exists in the Gawar area. It is practiced during the dry season on slightly and moderately eroded Fluvisols along the bank of the major rivers. The hazard to rain erosion is small, partly because of coarse textures (sand and silt) that resist compaction and reduce erosion, and partly because the agricultural activities are undertaken during the dry season only.

13.3 CONSERVATION AND CORRECTION LAND USE OPTION

The areas in which the soils are strongly eroding cannot secure a sustainable crop production. This appeals for corrective farming systems in which the activities related to intensive agriculture, sylviculture and livestock are in association and rotation. In fact, the intensive agro-sylvo-pastoral system can be considered as a transitional system, replacing the current extensive and shifting agriculture associated with extensive livestock on moderately eroded Lixisols, Planosols and Cambisols. Its advantage lies in increased land use diversity correlated with increased crop, fodder and fuelwood production.

The farmers can begin with an association of crops with trees in areas where measures controlling runoff and erosion are already well established. During annual cropping, the practice of cut-and-carry fodder (crop residues) from the cultivated areas is tentatively recommended. As soon as the trees become bigger (from year 3 or so) or when competition between crops and trees starts, annual cropping is abandoned to the benefit of improved pastures. Seeds of grass and legume pastures are sown to provide grazing for the cattle. During the development of the trees, the animals graze on this tree-pasture complex. The tree plantation must consist of useful trees for fodder, fuelwood and construction materials. Water ponds are built and regularly distributed to avoid sward trampling due to local concentration of the animals. After the tree production has reached a critical level (biomass decline associated with improved soil fertility), all the trees are chopped down. The area is then cleared for the next association of crops with trees, indicating the initiation of a new cycle of agro-sylvo-pastoral management. Follet and Stewart (1985), Hurni and Kebede (1992), De Graaff (1993) and De Graaff (1996) report the effectiveness of such a farming system.

13.4 RESTORATION AND REHABILITATION LAND USE OPTION

In the areas where soils are dramatically eroded and crop yields are very low, rehabilitative and restorative farming systems should prevail. The objective is to increase soil productivity and land use diversity rather than to stick to a specific, low-yielding activity. Increased land use diversity induces increased efficiency of resource utilization, internal nutrient cycling, and biological control process, both in space and time (Gliessman and Amador, 1980; Marshall and Willey, 1983). Barren soil-tolerant crop varieties have already been introduced, but their productivity is low and the system requires adjustments. Soil productivity and land use diversity can be increased on marginal lands in the Gawar area using three farming systems, including: (1) intensive rainfed agriculture associated with stall feeding livestock; (2) intensive sylvo-pastoral farming system; and (3) nature preserve.

13.4.1 Intensive rainfed agriculture associated with stall feeding livestock

The intensive rainfed agriculture associated with stall feeding livestock is a farming system in which intensive measures for soil and water management to restore and maintain soil fertility on severely eroded Vertisols are practised. This system is considered as a transitional system, that can replace the current extensive livestock associated with extensive firewood harvesting.

Management practices controlling erosion, conserving water by storage and improving infiltration include micro-catchment, tied ridging and ridge-furrow system. These land management practices have been tested in the Gawar area and proved to be effective in soil and water conservation and in biomass increase. Biological measures consist of mixed cropping and mulching. Soil fertility is maintained by the use of animal manure.

The livestock consists of raising small stocks around the house compounds, using stall feeding methods. Stall feeding prevents the runoff and erosion control measures to be damaged by animal movement. It also prevents the topsoil layer from pulverization and the subsoil layers from compaction, which decreases erosion.

13.4.2 Intensive sylvo-pastoral practices

The intensive sylvo-pastoral farming system is an integrated management system in which pastures are grown in combination with timber production. This is an improved system that can replace the current extensive livestock associated with extensive firewood harvesting, on severely eroded classes of Lixisols, Planosols and Cambisols.

The farmers begin with land management practices controlling runoff and soil loss. Then, the field is sown to grass pastures, legume pastures and trees, that have a quick growing and extensive plant cover to provide fodder, fuelwood and construction materials. Water ponds must be built and regularly distributed to avoid trampling due to local concentration of the animals.

13.4.3 Nature preserves and leisure areas

Steep highland slopes in the Gawar area are relatively unstable. As a consequence, natural forests should not be converted into areas of intensive human activities that cause substantial soil erosion. Nature preserves are suggested on severely eroded Leptosols on steep slopes. Finally, leisure or recreational areas can be created or expanded, since non-agricultural activities producing less soil erosion have a legitimate right to acquire land in rural upland areas and this right may be recognized and catered for.

CHAPTER 14

GENERAL CONCLUSIONS

Soil erosion is one of the major constraints to agricultural and livestock development in the semiarid zone of Cameroon, causing unmatched crop and animal productions and food requirements. Although many erosion studies have been carried out, most of the soil conservation programmes failed, probably because the models were borrowed from areas with different environmental conditions and erosion mechanisms. The current study was conducted in the Gawar area, in the semiarid zone of Cameroon. The area offers a variety of geomorphic units, soil types, cropping systems and management practices, and receives special governmental and non-governmental attention. Three spatial levels of the research were considered: (1) the watershed level, (2) the plot level, and (3) the micro-plot level. This chapter brings together the main conclusions reached during the research and presents some perspectives for the development of soil and water conservation strategies in the semiarid zone of Cameroon as a whole.

14.1 TESTING OF METHODS AND TECHNIQUES

There is a high variability in soil types as well as in erosion classes. Soils defined on the basis of erosion classes provide map units that are more uniform in terms of their properties than the soil types. This indicates a high consistency of the geopedologic approach in segregating map units at watershed level.

The spatial distribution of the erosion indicators along the slope helped identify the constraints to crop production and select appropriate soil and water conservation measures at plot level, whereas interrill erosion sub-processes were determined at micro-plot scale. In this context, geostatistics were useful in highlighting at what scale erosion processes vary and detecting changes in spatial variability of the erosion indicators.

Processes not discernible at watershed or plot scale, such as splash, crusting, denudation and micro-rilling, were determined in detail, allowing to develop an interrill erosion model that proved to be more consistent with local conditions and predict interrill soil loss better than the Kinnell model. The model accuracy was validated against the experiments conducted on small-sized plots with simulated rains.

14.2 RESULTS AT WATERSHED LEVEL

Six main soil types were found, including Lixisols, Vertisols, Cambisols, Leptosols, Fluvisols and Planosols. Erosion has caused modifications that have affected the surface soil properties, creating considerable variations within a given soil type. According to the degree of change, three erosion classes were identified and described: slightly, moderately, and severely eroded soils. Within each erosion class of a given soil type, the general tendency is that the thickness of the topsoil layer and coarse particle contents exhibit high variations, pH exhibits small variations, whereas organic matter and clay contents show intermediate variations. Differences in the degree of variation of the soil properties imply different sensitivities of these properties to changes caused by erosion. For many soil properties, the order of increasing degree of variation is indicated by slightly eroded soils < moderately eroded soils < severely eroded soils, suggesting that erosion causes the soil properties to change in such a way that more erosion takes place.

The land use diversity and the soil productivity decreased with increasing erosion severity. To curb land degradation, three land use options are proposed: (1) a preservation and protection land use option on less eroded and fertile soils; (2) a conservation and correction land use option on eroding soils; and (3) a rehabilitation and restoration land use option on more eroded and barren soils.

14.3 RESULTS AT PLOT LEVEL

The distribution of erosion indicators, including the properties of the topsoil, characteristics of the soil management and crop performance on moderately eroded Lixisols and moderately eroded Vertisols, are spatially dependent and modified by erosion. The values of many variables decrease as a function of the distance downslope. These relationships were more consistent on moderately eroded Lixisols than on moderately eroded Vertisols, suggesting that erosion can take place anywhere in the field on moderately eroded Vertisols. This behaviour provided two clues to determine the constraints to crop development and establish appropriate soil and water conservation measures. The first clue was about the area of actual damage as a percentage of the field size, giving an insight to whether soil conservation is needed to cover the whole field (for instance on moderately eroded Vertisols) or if a single measure can do as well (for instance on moderately eroded Lixisols). The second clue paid particular attention to the areas with high erosion severity to know where to place the soil conservation measures.

Although major soil types are already severely eroded, simple surface practices that are at the same time sound to the environment and economically profitable to the small farmers, as described in the sorghum experiments on severely eroded Vertisols, can increase grain sorghum yield by many orders of magnitude. Compared to productions normally achieved by farmers on severely eroded soils without surface management, the yields are 43 times higher on micro-catchment, 28 times higher on ridge furrow system, and 23 times higher on tied ridging This indicates that self-sufficient food production for human and animal populations could be achieved in the Gawar area with the help of internal and external incentives.

14.4 RESULTS AT MICRO-PLOT LEVEL

The research provides experimental procedures to quantify physical processes of interrill soil erosion and evaluate, against experimental data, the functional dependency of the mathematical solutions for various variables or factors of interrill erosion. A local model of interrill erosion was developed, which satisfies the requirement of comprehensiveness, in terms of the factors and erosion processes involved. It accounts for changes in rainfall, runoff and soil properties, that control stability of the soil surface aggregates and regulate permeability of the soil profile.

Compared to the Kinnell interrill erosion equation, the results of this study show that interrill erosion equation takes care of the interrill erodibility and interrill erodibility ranking among soils. The local model explains soil loss more successfully than the

Kinnell model. The accuracy in estimating the interrill soil erodibility by the local model was higher than that of the Kinnell model, indicating that the interrill soil erodibility factor has been derived from clearly identified erosion sub-processes.

Considering the local interrill soil erosion and interrill soil erodibility results, the following conclusions can be made:

- Interrill soil loss is a function of both rainfall amount and runoff amount, contrasting with interrill erosion equations that only consider rainfall and runoff intensities. Additionally, the inclusion of the soil surface resistance in the model has considerably improved the soil loss prediction.
- Soil particle detachment by overland flow can occur in the interrill areas.
- Processes, such as crusting, denudation and micro-rilling, can be detected and characterized in the interrill areas and their development and effect at plot scale can be predicted.
- Interrill soil loss varies significantly between rains, soil types and erosion classes, reflecting a dynamic interrill erosion process that changes with time due to changes in rainfall and runoff characteristics, soil properties and soil surface conditions.
- Interrill erodibility values account for both soil loss and runoff.
- Morphological and physical topsoil properties, such as structure, bulk density, clay and coarse particles, and chemical topsoil properties, including organic matter, calcium and phosphorus, are the best interrill erodibility predictors, indicating that properties controlling water movement and cohesion between soil particles play a major role in interrill erosion.

14.5 PERSPECTIVES

Although various spatial scales were considered in the current research, efforts to analyze the erosion mechanisms and formulate soil and water conservation strategies are still needed. Some of these efforts can be listed as follows.

14.5.1 Socio-cultural and economic aspects

Current erosion studies in the semiarid zone of Cameroon emphasize only physical aspects. Soil erosion is a multidisciplinary study domain, involving socio-cultural and economic aspects as well as physical ones. For instance, many farmers are reluctant to implement conservation measures, since they have to rely on their individual and limited resources, and avoid investing on land they can easily be moved away from. Research on the perception of land by farmers and on economic and social incentives to the farmers should be carried out for the adoption of soil conservation measures.

14.5.2 Physical aspects

The present study was confined to characterize interrill soil erosion and related soil erodibility. However, soil erosion is a complex process exposed to spatial and temporal changes. Although the developed local model improves interrill soil loss prediction, efforts are still needed in the following domains:

- Consideration of the slope length and slope gradient in the determination of interrill erosion for each erosion class of the major soil types;
- Consideration of seasonal variations of interrill erodibility, reflecting seasonal variations of the soil properties;
- Consideration of the local model as input data for the development of models predicting soil loss at plot and watershed scales, where all the other erosion factors are integrated.

The semiarid area of Cameroon in general and the Gawar study area in particular show a need for further multidisciplinary research on physical and socio-economic aspects of soil erosion for the design, implementation and adoption of appropriate strategies to combat soil erosion. Therefore, an appeal is made to promote cooperation at local, national and international levels in connection with further orientation of the research.

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ANNEXES

ANNEX A
TIME DISTRIBUTION OF INFILTRATION AND RUNOFF

A.1 INFILTRATION AND RUNOFF IN RAIN 2

A.1.1 On Lixisols

(1) Plots on slightly eroded Lixisols

Plot 7

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
16	8.2	8.2	0	0	0	8.2	8.2
21	3.3	11.5	7.2	0.6	0.6	2.7	10.9
35	9.3	20.8	15	3.5	4.1	5.8	16.7
45	6.7	27.5	21	3.5	7.6	3.2	19.9
47	2	29.5	30	1	8.6	1	20.9
64	17	46.5	34.6	9.8	18.4	7.8	28.7
75	11	57.5	27.6	5	23.4	6	34.7
77	1	58.5	24	0.4	23.8	0.6	35.3
90	6.5	65	15	3.2	27	3.3	38.6
91	0	65	6	0.1	27.1	-0.1	38.5

(2) Plot on moderately eroded Lixisols

Plot 3

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
24	13.5	13.5	0	0	0	13.5	13.5
32	5.3	18.8	4.3	0.5	0.5	4.8	18.3
37	3.3	22.1	12	1	1.5	2.3	20.6
43	4	26.1	18	1.8	3.3	2.2	22.8
45	1.4	27.5	27	0.9	4.2	0.5	23.3
47	2	29.5	30	1	5.2	1	24.3
49	2	31.5	42	1.4	6.6	0.6	24.9
51	2	33.5	45	1.5	8.1	0.5	25.4
67	16	49.5	43.8	11.7	19.8	4.3	29.7
73	6	55.5	51	5.1	24.9	0.9	30.6
75	2	57.5	36	1.2	26.1	0.8	31.4
77	1	58.5	12	0.4	26.5	0.6	32
90	6.5	65	9	1.9	28.4	4.6	36.6
91	0	65	6	0.1	28.5	-0.1	36.5

Plot 4

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
19	10.2	10.2	0	0	0	10.2	10.2
21	1.3	11.5	9	0.3	0.3	1	11.2
23	1.3	12.8	12	0.4	0.7	0.9	13.1
25	1.3	14.1	9	0.3	1	1	14.1
31	4	18.1	15	1.5	2.5	2.5	16.6
45	9.3	27.4	9.8	2.3	4.8	7	23.6
51	6	33.4	15	1.5	6.3	4.5	28.1
59	8	41.4	18	2.4	8.7	5.6	33.7
71	12	53.4	19	3.8	12.5	8.2	41.9
73	2	55.4	24	0.8	13.3	1.2	43.1
77	3	58.4	21	1.4	14.7	1.6	44.7
79	1	59.4	15	0.5	15.2	0.5	45.2
90	5.6	65	10	1.8	17	3.8	49
91	0	65	3	0	17	0	49

Plot 14

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
17	8.8	8.8	0	0	0	8.8	8.8
21	2.7	11.5	2.4	0.1	0.1	2.6	11.4
32	7.3	18.8	4.8	0.9	1	6.4	17.8
36	2.7	21.5	9	0.6	1.6	2.1	19.9
46	7	28.5	12	2	3.6	5	24.9
58	12	40.5	15	3	6.6	9	33.9
66	8	48.5	16.5	2.2	8.8	5.8	39.7
75	9	57.5	18	2.7	11.5	6.3	46
84	4.5	62	15	2.2	13.7	2.3	48.3
90	3	65	12	1.2	14.9	1.8	50.1
91	0	65	6	0.1	15	-0.1	50

Plot 18

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
6	3	3	0	0	0	3	3
8	1	4	18	0.6	0.6	0.4	3.4
12	2	6	15	1	1.6	1	4.4
15	1.5	7.5	24	1.2	2.8	0.3	4.7
24	6	13.5	28.2	4.2	7	1.8	6.5
45	14	27.5	36.6	12.8	19.8	1.2	7.7
66	21	48.5	43.6	15.2	35	5.8	13.5
70	4	52.5	48	3.2	38.2	0.8	14.3
75	5	57.5	45	3.7	41.9	1.3	15.6
80	2.5	60	30	2.5	44.4	0	15.6
90	5	65	27	4.5	48.9	0.5	16.1
91	0	65	12	0.2	49.1	-0.2	15.9

Plot 24

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
17	8.8	8.8	0	0	0	8.8	8.8
22	3.4	12.2	4.8	0.4	0.4	3	11.8
24	1.3	13.5	9	0.3	0.7	1	12.8
26	1.3	14.8	15	0.5	1.2	0.8	13.6
28	1.3	16.1	9	0.3	1.5	1	14.6
30	1.3	17.4	12	0.4	1.9	0.9	15.5
38	5.4	22.8	18	2.4	4.3	3	18.5
42	2.7	25.5	21	1.4	5.7	1.3	19.8
46	3	28.5	24	1.6	7.3	1.4	21.2
54	8	36.5	36	4.8	12.1	3.2	24.4
66	12	48.5	38	7.6	19.7	4.4	28.8
75	9	57.5	42	6.3	26	2.7	31.5
78	1.5	59	30	1.5	27.5	0	31.5
90	6	65	23.5	4.7	32.2	1.3	32.8
91	0	65	12	0.2	32.4	-0.2	32.6

(3) Plots on severely eroded Lixisols

Plot 16

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
21	11.5	11.5	0	0	0	11.5	11.5
26	3.3	14.8	4.8	0.4	0.4	2.9	14.4
46	13.7	28.5	3.6	1.2	1.6	12.5	26.9
51	5	33.5	4.8	0.4	2	4.6	31.5
81	27	60.5	6	3	5	24	55.5
90	4.5	65	4.7	0.7	5.7	3.8	59.3
91	0	65	0	0	5.7	0	59.3

Plot 19

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
29	16.8	16.8	0	0	0	16.8	16.8
34	3.3	20.1	7.2	0.6	0.6	2.7	19.5
36	1.3	21.4	9	0.3	0.9	1	20.5
43	4.7	26.1	15	1.7	2.6	3	23.5
52	8.4	34.5	22.5	3.3	5.9	5.1	28.6
68	16	50.5	25.5	6.8	12.7	9.2	37.8
72	4	54.5	30	2	14.7	2	39.8
76	3.5	58	25.5	1.7	16.4	1.8	41.6
90	7	65	22.5	5.2	21.6	1.8	43.4
91	0	65	12	0.2	21.8	-0.2	43.2

A.1.2 On Vertisols

(1) Plots on slightly eroded Vertisols

Plot 6

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
15	7.5	7.5	0	0	0	7.5	7.5
45	20	27.5	0	0	0	20	27.5
75	30	57.5	0	0	0	30	57.5
90	7.5	65	0	0	0	7.5	65

(2) Plots on moderately eroded Vertisols

Plot 11

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
20	10.8	10.8	0	0	0	10.8	18.8
25	3.3	14.1	4.8	0.4	0.4	2.9	13.7
30	3.3	17.4	15.6	1.3	1.7	2	15.7
40	6.7	24.1	20.4	3.4	5.1	3.3	19
62	20.4	44.5	24.5	9	14.1	11.4	30.4
68	6	50.5	27	2.7	16.8	3.3	33.7
72	4	54.5	30	2	18.8	2	35.7
82	6.5	61	27	4.5	23.3	2	37.7
90	4	65	24	3.2	26.5	0.8	38.5
91	0	65	12	0.2	26.7	-0.2	38.3

Plot 17

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
27	15.5	15.5	0	0	0	15.5	15.5
32	3.4	18.9	10.8	0.9	0.9	2.5	18
34	1.3	20.2	12	0.4	1.3	0.9	18.9
36	1.3	21.5	15	0.5	1.8	0.8	19.7
42	4	25.5	18	1.8	3.6	2.2	21.9
48	5	30.5	24	2.4	6	2.6	24.5
60	12	42.5	31.5	6.3	12.3	5.7	30.2
75	15	57.5	38.2	8.2	20.5	6.8	37
78	1.5	59	30	1.5	22	0	37
90	6	65	27	5.4	27.4	0.6	37.6
91	0	65	6	0.1	27.5	-0.1	37.5

(3) Plot on severely eroded Vertisols

Plot 21

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
49	31.5	31.5	0	0	0	31.5	31.5
54	5	36.5	4.8	0.4	0.4	4.6	36.1
59	5	41.5	2.4	0.2	0.6	4.8	40.9
64	5	46.5	3.6	0.3	0.9	4.7	45.6
69	5	51.5	6	0.5	1.4	4.5	50.1
79	8	59.5	7.2	1.2	2.6	6.8	56.9
84	2.5	62	4.8	0.4	3	2.1	59
90	3	65	7.2	0.7	3.7	2.3	61.3
91	0	65	0	0	3.7	0	61.3

A.1.3 On Cambisols

(1) Plots on slightly eroded Cambisols

Plot 2

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
49	35.1	31.5	0	0	0	31.5	31.5
65	16	47.5	3.7	1	1	15	46.5
77	11	58.5	6	1.2	2.2	9.8	56.3
90	6.5	65	0.9	0.2	2.4	6.3	62.6
91	0	65	0	0	2.4	0	62.6

Plot 23

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
15	7.5	7.5	0	0	0	7.5	7.5
45	20	27.5	0	0	0	20	27.5
75	30	57.5	0	0	0	30	57.5
90	7.5	65	0	0	0	7.5	65

(2) Plots on moderately eroded Cambisols

Plot 10

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
14	7	7	0	0	0	7	7
19	3.2	10.2	6	0.5	0.5	2.7	9.7
25	4	14.2	12	1.2	1.7	2.8	12.5
33	5.3	19.5	15	2	3.7	3.3	15.8
43	6.7	26.2	18	3	6.7	3.7	19.5
49	5.3	31.5	20	2	8.7	3.3	22.8
65	16	47.5	25.5	6.8	15.5	9.2	37.3
75	10	57.5	27	4.5	20	5.5	42.8
90	7.5	65	21	5.2	25.2	2.3	45.1
91	0	65	6	0.1	25.3	-0.1	45

Plot 20

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
16	8.2	8.2	0	0	0	8.2	8.2
21	3.3	11.5	4.8	0.4	0.4	2.9	11.1
23	1.3	12.8	9	0.3	0.7	1	12.1
31	5.3	18.1	12	1.6	2.3	3.7	15.8
37	4	22.1	17	1.7	4	2.3	18.1
42	3.4	25.5	21	1.7	5.7	1.7	19.8
53	10	35.5	27	4.9	10.6	5.1	24.9
63	10	45.5	34.8	5.8	16.4	4.2	29.1
75	12	57.5	40	8	24.4	4	33.1
85	5	62.5	30	5	29.4	0	33.1
90	2.5	65	27	2.2	31.6	0.3	33.4
91	0	65	18	0.3	31.9	-0.3	33.1

(3) Plots on severely eroded Cambisols

Plot 1

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
21	11.5	11.5	0	0	0	11.5	11.5
23	1.3	12.8	18	0.6	0.6	0.7	12.2
36	8.7	21.5	15	3.2	3.8	5.5	17.7
39	2	23.5	21	1	4.8	1	18.7
45	4	27.5	18	1.8	6.6	2.2	20.9
47	2	29.5	24	0.8	7.4	1.2	22.1
73	26	55.5	31.6	13.7	21.1	12.3	34.4
75	2	57.5	36	1.2	22.3	0.8	35.2
79	2	59.5	19.5	1.3	23.6	0.7	35.9
90	5.5	65	15	2.7	26.3	2.8	38.7
91	0	65	6	0.1	26.4	-0.1	38.6

Plot 5

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
24	13.5	13.5	0	0	0	13.5	13.5
32	5.3	18.8	4	0.5	0.5	4.8	18.3
36	2.7	21.5	6	0.4	0.9	2.3	20.6
38	1.3	22.8	15	0.5	1.4	0.8	21.4
46	5.7	28.5	9	1.2	2.6	4.5	25.9
50	4	32.5	22.5	1.5	4.1	2.5	28.4
60	10	42.5	28.5	4.7	8.8	5.3	33.7
62	2	44.5	36	1.2	10	0.8	34.5
76	13.5	58	27.8	6.5	16.5	7	41.5
90	7	65	16.5	3.8	20.3	3.2	44.7
91	0	65	6	0.1	20.4	-0.1	44.6

A.1.4 On Fluvisols

(1) Plot on slightly eroded Fluvisols

Plot 9

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
44	26.8	26.8	0	0	0	26.8	26.8
49	4.7	31.5	2.4	0.2	0.2	4.5	31.3
54	5	36.5	4.8	0.4	0.6	4.6	35.9
59	5	41.5	7.2	0.6	1.2	4.4	40.3
64	5	46.5	10.8	0.9	2.1	4.1	44.5
75	11	57.5	18	3.3	5.4	7.7	52.2
90	7.5	65	9	2.2	7.6	5.3	57.5
91	0	65	3	0	7.6	0	57.5

(2) Plot on moderately eroded Fluvisols

Plot 22

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
32	18.8	18.8	0	0	0	18.8	18.8
42	6.7	25.5	6	1	1	5.7	24.5
70	27	52.5	27	12.6	13.6	14.4	38.9
75	5	57.5	30	2.5	16.1	2.5	41.4
77	1	58.5	27	0.9	17	0.1	41.5
90	6.5	65	15	3.2	20.2	3.3	44.8
91	0	65	6	0.1	20.3	0.1	44.7

A.1.5 On severely eroded Leptosols

Plot 12

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
15	7.5	7.5	0	0	0	7.5	7.5
20	3.3	10.8	7.2	0.6	0.6	2.7	10.2
26	4	14.8	12	1.2	1.8	2.8	13
28	1.3	16.1	15	0.5	2.3	0.8	13.8
38	6.7	22.8	19.2	3.2	5.5	3.5	17.3
48	7.7	30.5	21.6	3.6	9.1	4.1	21.4
70	22	52.5	27.2	9.9	19	12.1	33.5
78	6.5	59	26.2	3.5	22.5	3	36.5
90	6	65	21	4.2	26.7	1.8	38.3
91	0	65	6	0.1	26.8	-0.1	38.2

A.1.6 On Planosols

(1) Plots on slightly eroded Planosols

Plot 15

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
16	8.2	8.2	0	0	0	8.2	8.2
21	3.3	11.5	4.8	0.4	0.4	2.9	11.1
25	2.7	14.2	15	1	1.4	1.7	12.8
31	4	18.2	19	1.9	3.3	2.1	14.9
41	6.7	24.9	21.6	3.6	6.9	3.1	18
63	20.6	45.5	27	9.9	16.8	10.7	28.7
75	12	57.5	28	5.6	22.4	6.4	35.1
90	7.5	65	19.5	4.8	27.2	2.7	37.8
91	0	65	6	0.1	27.3	-0.1	37.7

(2) Plot on moderately eroded Planosols

Plot 13

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
18	9.5	9.5	0	0	0	9.5	9.5
23	3.3	12.8	6	0.5	0.5	2.8	12.3
28	3.3	16.1	13.2	1.1	1.6	2.2	14.5
36	5.4	21.5	16.5	2.2	3.8	3.2	17.7
46	7	28.5	20.4	3.4	7.2	3.6	21.3
56	10	38.5	33	5.5	12.7	4.5	24.8
75	19	57.5	34.8	11	23.7	8	33.8
90	7.5	65	19.1	4.7	28.4	2.8	36.6
91	0	65	6	0.1	28.5	-0.1	36.5

(3) Plot on severely eroded Planosols

Plot 8

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
14	7	7	0	0	0	7	7
24	6.5	13.5	5	0.8	0.8	5.7	12.7
29	3.3	16.8	6	0.5	1.3	2.8	15.5
45	10.7	27.5	15	4	5.3	6.7	22.2
47	2	29.5	21	0.7	6	1.3	23.5
55	8	37.5	27	3.6	9.6	4.4	27.9
75	20	57.5	30	10	19.6	10	37.9
90	7.5	65	15	3.7	23.3	3.8	41.7
91	0	65	6	0.1	23.4	-0.1	41.6

Plot 25

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
15	7.5	7.5	0	0	0	7.5	7.5
20	3.3	10.8	7.2	0.6	0.6	2.7	10.2
40	13.4	24.2	19.2	6.4	7	7	17.2
46	4.3	28.5	26	2.6	9.6	1.7	18.9
75	29	57.5	36.6	17.7	27.3	11.3	30.2
90	7.5	65	24	6	33.3	1.5	31.7
91	0	65	12	0.2	33.5	-0.2	31.5

A.2 INFILTRATION AND RUNOFF IN RAIN 3

A.2.1 On lixisols

(1) Plot on slightly eroded Lixisols

Plots 7

Time Interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
4	2	2	0	0	0	2	2
11	3.5	5.5	12	1.4	1.4	2.1	4.1
15	2	7.5	16.5	1.1	2.5	0.9	5
17	2	9.5	21	0.7	3.2	1.3	6.3
19	2	11.5	30	1	4.2	1	7.3
47	28.7	40.2	32.3	15	19.2	13.7	21
63	21.3	61.5	49.8	13.3	32.5	8	29
69	8	69.5	53	5.3	37.8	2.7	31.7
75	8	77.5	51	5.1	42.9	2.9	34.6
79	2	79.5	30	2	44.9	0	34.6
85	3	82.5	27	2.7	47.6	0.3	34.9
90	2.5	85	24	2	49.6	0.5	35.4
91	0	85	12	0.2	49.8	-0.2	35.2

(2) Plots on moderately eroded Lixisols

Plot 3

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
7	3.5	3.5	0	0	0	3.5	3.5
11	2	5.5	2.4	0.1	0.1	1.9	5.4
13	1	6.5	12	0.4	0.5	0.6	6
17	3	9.5	18	1.2	1.7	1.8	7.8
47	30.7	40.2	27.8	13.9	15.6	16.8	24.6
55	10.6	50.8	39	5.2	20.8	5.4	30
75	26.7	77.5	40.2	13.4	34.2	13.3	43.3
77	1	78.5	30	1	35.2	0	43.3
85	4	82.5	21.7	2.9	38.1	1.1	44.4
90	2.5	85	21	1.7	39.8	0.8	45.2
91	0	85	6	0.1	39.9	-0.1	45.1

Plot 4

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
4	2	2	0	0	0	2	2
12	4	6	7.5	1	1	3	5
16	2.5	8.5	12	0.8	1.8	1.7	6.7
56	43.7	52.2	26.7	17.8	19.6	25.9	32.6
66	13.3	65.5	42	7	26.6	6.3	38.9
75	12	77.5	35.4	5.3	31.9	6.7	45.6
80	2.5	80	22.5	1.8	33.7	0.7	46.3
90	5	85	15.5	2.6	36.3	2.4	48.7
91	0	85	6	0.1	36.4	-0.1	48.6

Plot 14

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
1	0.5	0.5	0	0	0	0.5	0.5
3	1	1.5	24	0.8	0.8	0.2	0.7
15	6	7.5	27	5.4	6.2	0.6	1.3
19	4	11.5	34.5	2.3	8.5	1.7	3
47	28.7	40.2	41.1	19.2	27.7	9.5	12.5
51	5.3	45.5	52.5	3.5	31.2	1.8	14.3
63	16	61.5	54	10.8	42	5.2	19.5
75	16	77.5	53	10.6	52.6	5.4	24.9
77	1	78.5	30	1	53.6	0	24.9
90	6.5	85	24	5.2	58.8	1.3	26.2
91	0	85	6	0.1	58.9	-0.1	26.1

Plot 18

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
2	1	1	0	0	0	1	1
7	2.5	3.5	24	2	2	0.5	1.5
17	6	9.5	27	4.5	6.5	1.5	3
19	2	11.5	36	1.2	7.7	0.8	3.8
47	28.7	40.2	45.2	21.1	28.8	7.6	11.4
75	37.3	77.5	61.9	28.9	57.7	8.4	19.8
81	3	80.5	30	3	60.7	0	19.8
90	4.5	85	28.2	4.2	64.9	0.3	20.1
91	0	85	18	0.3	65.2	-0.3	19.8

Plot 24

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
2	1	1	0	0	0	1	1
4	1	2	9	0.3	0.3	0.7	1.7
16	6.5	8.5	27	5.4	5.7	1.1	2.8
46	30.3	38.8	48.4	24.2	29.9	6.1	8.9
66	26.7	65.5	66	22	51.9	4.7	13.6
70	5.3	70.8	70.5	4.7	56.6	0.6	14.2
75	6.7	77.5	66	5.5	62.1	1.2	15.4
82	3.5	81	30	3.5	65.6	0	15.4
90	4	85	27	3.6	69.2	0.4	15.8
91	0	85	12	0.2	69.4	-0.2	15.6

(3) Plots on severely eroded Lixisols

Plot 16

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
5	2.5	2.5	0	0	0	2.5	2.5
10	2.5	5	8.4	0.7	0.7	1.8	4.3
15	2.5	7.5	6	0.5	1.2	2	6.3
19	4	11.5	9	0.6	1.8	3.4	9.7
37	18	29.5	13.3	4	5.8	14	23.7
47	10.7	40.2	18.6	3.1	8.9	7.6	31.3
71	32	72.2	37.2	14.9	23.8	17.1	48.4
75	5.3	77.5	48	3.2	27	2.1	50.5
90	7.5	85	19.8	4.9	31.9	2.6	53.1
91	0	85	6	0.1	32	-0.1	53

Plot 19

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
5	2.5	2.5	0	0	0	2.5	2.5
7	1	3.5	12	0.4	0.4	0.6	3.1
9	1	4.5	18	0.6	1	0.4	3.5
15	3	7.5	24	2.4	3.4	0.6	4.1
45	30	37.5	38	19	22.4	11	15.1
47	2.7	40.2	42	1.3	23.7	1.4	16.5
75	37.3	77.5	55.9	26.1	49.8	11.2	27.7
79	2	79.5	30	2	51.8	0	27.7
81	1	80.5	27	0.9	52.7	0.1	27.8
90	4.5	85	23.4	3.5	56.2	1	28.8
91	0	85	12	0.2	56.4	-0.2	28.6

A.2.2 On Vertisols

(1) Plot on slightly eroded Vertisols

Plot 6

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
15	7.5	7.5	0	0	0	7.5	7.5
45	30	37.5	0	0	0	30	37.5
75	40	77.5	0	0	0	40	77.5
90	7.5	85	0	0	0	7.5	85

(2) Plots on moderately eroded Vertisols

Plot 11

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
5	2.5	2.5	0	0	0	2.5	2.5
7	1	3.5	18	0.6	0.6	0.4	2.9
11	2	5.5	21	1.4	2	0.6	3.5
15	2	7.5	24	1.6	3.6	0.4	3.9
19	4	11.5	30	2	5.6	2	5.9
47	28.7	40.2	34	15.8	21.4	12.9	18.8
75	37.3	77.5	46.8	21.8	43.2	15.5	34.3
79	2	79.5	30	2	45.2	0	34.3
90	5.5	85	28	5.1	50.3	0.4	34.7
91	0	85	12	0.2	50.5	-0.2	34.5

Plot 17

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
3	1.5	1.5	0	0	0	1.5	1.5
8	2.5	4	10.8	0.9	0.9	1.6	3.1
13	2.5	6.5	19.2	1.6	2.5	0.9	4
15	1	7.5	21	0.7	3.2	0.3	4.3
27	12	19.5	37.5	7.5	10.7	4.5	8.8
61	39.3	58.8	45.3	25.6	36.3	13.7	22.5
67	8	66.8	65	6.5	42.8	1.5	24
75	10.7	77.5	68	9	51.8	1.7	25.7
77	1	78.5	30	1	52.8	0	25.7
90	6.5	85	27	5.8	58.6	0.7	26.4
91	0	85	18	0.3	58.9	-0.3	26.1

(3) Plot on severely eroded Vertisols

Plot 21

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
3	1.5	1.5	0	0	0	1.5	1.5
7	2	3.5	9	0.6	0.6	1.4	2.9
11	2	5.5	13.5	0.9	1.5	1.1	4
15	2	7.5	25.5	1.7	3.2	0.3	4.3
23	8	15.5	36.7	4.9	8.1	3.1	7.4
33	10	25.5	42	7	15.1	3	10.4
39	6	31.5	45	4.5	19.6	1.5	11.9
47	8.7	40.2	47.2	6.3	25.9	2.4	14.3
61	18.6	58.8	58.7	13.7	39.6	4.9	19.2
65	5.3	64.1	69	4.6	44.2	0.7	19.9
75	13.4	77.5	63.6	10.6	54.8	2.8	22.7
79	2	79.5	30	2	56.8	0	22.7
90	5.5	85	27	4.9	61.7	0.6	23.3
91	0	85	12	0.2	61.9	-0.2	23.1

A.2.3 On Cambisols

(1) Plots on slightly eroded Cambisols

Plot 2

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
12	6	6	0	0	0	6	6
17	3.5	9.5	4.8	0.4	0.4	3.1	9.1
19	2	11.5	9	0.3	0.7	1.7	10.8
21	2	13.5	12	0.4	1.1	1.6	12.4
45	24	37.5	18.5	7.4	8.5	16.6	29
63	24	61.5	31.6	6.3	14.8	17.7	46.7
67	5.3	66.8	36	2.4	17.2	2.9	49.6
75	10.7	77.5	30.7	4.1	21.3	6.6	56.2
77	1	78.5	24	0.8	22.1	0.2	56.4
90	6.5	85	6	1.3	23.4	5.2	61.6
91	0	85	0	0	23.4	0	61.6

Plot 23

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
45	37.5	37.5	0	0	0	37.5	37.5
50	6.7	44.2	4.8	0.4	0.4	6.3	43.8
52	2.6	46.8	6	0.2	0.6	2.4	46.2
64	16	62.8	12	2.4	3	13.6	59.8
75	14.7	77.5	18.6	3.4	6.4	11.3	71.1
78	1.5	79	6	0.3	6.7	1.2	72.3
80	1	80	3	0.1	6.8	0.9	73.2
90	5	85	2.4	0.4	7.2	4.6	77.8
91	0	85	0	0	7.2	0	77.8

(2) Plots on moderately eroded Cambisols

Plot 10

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
1	0.5	0.5	0	0	0	0.5	0.5
3	1	1.5	9	0.3	0.3	0.7	1.2
5	1	2.5	15	0.5	0.8	0.5	1.7
7	1	3.5	18	0.6	1.4	0.4	2.1
11	2	5.5	24	1.6	3	0.4	2.5
21	8	13.5	26.4	4.4	7.4	3.6	6.1
47	26.7	40.2	33.2	14.4	21.8	12.3	18.4
57	13.3	53.5	44.4	7.4	29.3	5.9	24.3
61	5.3	58.8	49.5	3.3	32.5	2	26.3
75	18.7	77.5	43.7	10.2	42.7	8.5	34.8
77	1	78.5	30	1	43.7	0	34.8
90	6.5	85	26.1	5.6	49.3	0.9	35.7
91	0	85	6	0.1	49.4	-0.1	35.6

Plot 20

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
2	1	1	0	0	0	1	1
4	1	2	9	0.3	0.3	0.7	1.7
10	3	5	21	2.1	2.4	0.9	2.6
14	2	7	27	1.8	4.2	0.2	2.8
16	1.5	8.5	30	1	5.2	0.5	3.3
18	2	10.5	42	1.4	6.6	0.6	3.9
46	28.3	38.8	46.5	21.7	28.3	6.6	10.5
48	2.7	41.5	66	2.2	30.5	0.5	11
56	10.7	52.2	69	9.2	39.7	1.5	12.5
75	25.3	77.5	66.6	21.1	60.8	4.2	16.7
77	1	78.5	30	1	61.8	0	16.7
90	6.5	85	27	5.8	67.6	0.7	17.4
91	0	85	18	0.3	67.9	-0.3	17.1

(3) Plots on severely eroded Cambisols

Plot 1

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
3	1.5	1.5	0	0	0	1.5	1.5
5	1	2.5	3	0.1	0.1	0.9	2.4
7	1	3.5	6	0.2	0.3	0.8	3.2
13	3	6.5	10	1	1.3	2	5.2
15	1	7.5	15	0.5	1.8	0.5	5.7
17	2	9.5	18	0.6	2.4	1.4	7.1
47	30.7	40.2	26.2	13.1	15.5	17.6	24.7
49	2.6	42.8	45	1.5	17	1.1	25.8
57	10.7	53.5	48	6.4	23.4	4.3	30.1
59	2.6	56.1	57	1.9	25.3	0.7	30.8
69	13.4	69.5	54	9	34.3	4.4	35.2
75	8	77.5	48.7	4.9	39.2	3.1	38.3
83	4	81.5	22	2.9	42.1	1.1	39.4
90	3.5	85	19.5	2.2	44.3	1.3	40.7
91	0	85	6	0.1	44.4	-0.1	40.6

Plot 5

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
5	2.5	2.5	0	0	0	2.5	2.5
11	3	5.5	8	0.8	0.8	2.2	4.7
17	4	9.5	20	2	2.8	2	6.7
35	18	27.5	28.3	8.5	11.3	9.5	16.2
51	26.7	45.5	31.5	8.4	19.7	9.6	25.8
71	2.6	72.2	45.6	15.2	34.9	11.5	37.3
73	2.7	74.8	51	1.7	36.6	0.9	38.2
75	7.5	77.5	48	1.6	38.2	1.1	39.3
90	0	85	20.5	5.1	43.3	2.4	41.7
91		85	6	0.1	43.4	-0.1	41.6

A.3.4 On Fluvisols

(1) Plots on slightly eroded Fluvisols

Plot 9

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
17	9.5	9.5	0	0	0	9.5	9.5
21	4	13.5	9	0.6	0.6	13.4	12.9
35	14	27.5	11.5	2.7	3.3	11.3	24.2
47	12.7	40.2	15	3	6.3	9.7	33.9
69	29.3	69.5	30.2	11	17.3	19.3	53.2
75	8	77.5	33	3.3	20.6	4.7	57.9
77	1	78.5	21	0.7	21.3	0.3	58.2
90	6.5	85	9	1.9	23.2	4.6	62.8
91	0	85	3	0	23.2	0	62.8

(2) Plots on moderately eroded Fluvisols

Plot 22

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
3	1.5	1.5	0	0	0	1.5	1.5
5	1	2.5	9	0.3	0.3	0.7	2.2
11	3	5.5	17	1.7	2	1.3	3.5
17	4	9.5	21	2.1	4.1	1.9	5.4
25	8	17.5	38.2	5.1	9.2	2.9	8.3
47	22.7	40.2	42.5	15.6	24.8	7.1	15.4
53	8	48.2	48	4.8	29.6	3.2	18.6
69	21.3	69.5	58.1	15.5	45.1	5.8	24.4
75	8	77.5	60	6	51.1	2	26.4
77	1	78.5	30	1	52.1	0	26.4
90	6.5	85	27	5.8	57.9	0.7	27.1
91	0	85	12	0.2	58.1	-0.2	26.9

A.2.5 On severely eroded Leptosols

Plot 12

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
5	2.5	2.5	0	0	0	2.5	2.5
7	1	3.5	6	0.2	0.2	0.8	3.3
15	4	7.5	22.5	3	3.2	1	4.3
17	2	9.5	27	0.9	4.1	1.1	5.4
47	30.7	40.2	32.2	16.1	20.2	14.6	20
53	8	48.2	37	3.7	23.9	4.3	24.3
59	8	56.2	42	4.2	28.1	3.8	28.1
75	21.3	77.5	39.7	10.6	38.7	10.7	38.8
77	1	78.5	30	1	39.7	0	38.8
90	6.5	85	27	5.8	45.5	0.7	39.5
91	0	85	12	0.2	45.7	-0.2	39.3

A.2.6 On Planosols

(1) Plots on slightly eroded Planosols

Plot 15

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
2	1	1	0	0	0	1	1
4	1	2	15	0.5	0.5	0.5	1.5
12	4	6	27	3.6	4.1	0.4	1.9
16	2.5	8.5	30	2	6.1	0.5	2.4
48	33	41.5	41	21.8	27.9	11.2	13.6
75	36	77.5	45	20.2	48.1	15.8	29.4
86	5.5	83	30	5.5	53.6	0	29.4
90	2	85	27	1.8	55.4	0.2	29.6
91	0	85	12	0.2	55.6	-0.2	29.4

(2) Plots on moderately eroded Planosols

Plot 13

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
1	0.5	0.5	0	0	0	0.5	0.5
11	5	5.5	22.4	3.7	3.7	1.3	1.8
13	1	6.5	24	0.8	4.5	0.2	2
17	3	9.5	31.5	2.1	6.6	0.9	2.9
39	22	31.5	44.1	16.1	22.7	5.9	8.8
47	8.7	40.2	52.5	7	29.7	1.7	10.5
61	18.7	58.9	59.5	13.9	43.6	4.8	15.3
75	18.6	77.5	62.1	14.5	58.1	4.1	19.4
83	4	81.5	30	4	62.1	0	19.4
90	3.5	85	27	3.1	65.2	0.4	19.8
91	0	85	12	0.2	65.4	-0.2	19.6

(3) Plots on severely eroded Planosols

Plot 8

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
7	3.5	3.5	0	0	0	3.5	3.5
13	3	6.5	2.4	0.2	0.2	2.8	6.3
19	5	11.5	6	0.6	0.8	4.4	10.7
21	2	13.5	24	0.8	1.6	1.2	11.9
23	2	15.5	27	0.9	2.5	1.1	13
51	30	45.5	36	16.8	19.3	13.2	26.2
53	2.7	48.2	42	1.4	20.7	1.3	27.5
75	29.3	77.5	45	16.5	37.2	12.8	40.3
77	1	78.5	30	1	38.2	0	40.3
79	1	79.5	27	0.9	39.1	0.1	43.4
81	1	80.5	21	0.7	39.8	0.3	43.7
90	4.5	85	12.6	1.9	41.7	2.6	46.3
91	0	85	6	0.1	41.8	-0.1	46.2

Plot 25

Time interval (minute)	Incremental rainfall (mm)	Cumulative rainfall (mm)	Instantaneous runoff (mm/h)	Incremental runoff (mm)	Cumulative runoff (mm)	Incremental storage (mm)	Cumulative storage (mm)
1	0.5	0.5	0	0	0	0.5	0.5
6	2.5	3	21.6	1.8	1.8	0.7	1.2
12	3	6	24	2.4	4.2	0.6	1.8
15	1.5	7.5	27	1.3	5.5	0.2	2
46	31.3	38.8	42.6	22	27.5	9.3	11.3
64	24	62.8	66	19.8	47.3	4.2	15.5
72	10.7	73.5	69.7	9.3	56.6	1.4	16.9
75	4	77.5	66	3.3	59.9	0.7	17.6
90	7.5	85	27	6.7	66.6	0.8	18.4
91	0	85	18	0.2	66.9	-0.3	18.1

A.3 ANTECEDENT SOIL MOISTURE CONTENT

Soil types	Erosion classes	Plot	Antecedent soil moisture content (weight %)					
			Before rain 2			Before rain 3		
			10 cm	20 cm	30 cm	10 cm	20 cm	30 cm
Alfisols	Slightly eroded	7	7.1	9.3	7.3	16.2	12.5	7.2
	Moderately eroded	3	10.9	10.2	6	9	10.7	10.7
		4	7	9.8	11.4	11.5	15	13.4
		14	1.8	2.4	9.8	10.3	10.2	12
		18	3.2	3.4	11	10.2	10.7	14.6
		24	6.6	6.6	15.1	15.9	15.2	17.8
	Severely eroded	16	2.9	4.9	4.3	17.6	15.9	14.5
		19	2.7	5.2	5.3	17.5	13.4	9.3
Vertisols	Slightly eroded	6	10	20.6	19.7	18.1	25	26.4
	Moderately eroded	11	16	9.8	11.9	16.1	13	11.2
		17	11.2	15.2	16.2	21.1	20.7	20
	Severely eroded	21	10.6	8.6	8.4	20.7	20.8	19.2
Inceptisols	Slightly eroded	2	9.5	8.9	10	15.4	21.5	20.9
		23	7.1	11.3	15.1	19.6	18.6	19
	Moderately eroded	10	6	5	5.8	15.2	12.8	13.3
		20	6.4	8.1	8.5	25.1	21.2	10.1
	Severely eroded	1	6.6	4.3	7.3	10.5	5.1	8.1
		5	11.5	10.5	7.5	16.6	16	17.2
Entisols	Slightly eroded	9	15.2	8.7	27.4	13.4	20.4	31
	Moderately eroded	22	3.5	2.3	1.6	18.3	16	5.7
	Severely eroded	12	1.2	-	-	15.4	-	-
Planosols	Slightly eroded	15	6.4	5.5	7.3	14	14.8	8.5
	Moderately eroded	13	2.3	2.5	3	11.5	9.9	8.5
	Severely eroded	8	1.6	3.9	4.2	15	6.2	5.4
		25	5.7	6.6	12.8	16.7	11.6	14

ANNEX B
TIME DISTRIBUTION OF EROSION PARAMETERS

B.1 EROSION PARAMETER VALUES IN RAIN 2

B.1.1 On Lixisols

(1) Plot on slightly eroded Lixisols

Plot 7

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	30.4	30.4	0	0	0	0	63
20	18.1	48.5	2.5	0.5	1.2	1.2	
30	15	63.5	1.5	2.4	3.6	4.8	
40	19.8	83.3	1.2	3	3.6	8.4	
50	19.8	103.1	1.1	4.5	5	13.4	
60	17.6	120.7	1.2	5.8	7	20.4	
70	14.5	135.2	1.1	5.5	6.1	26.5	
80	12	147.2	0.6	3.4	2	28.5	
90	6.6	153.8	0.3	2.4	0.7	29.2	

(2) Plots on moderately eroded Lixisols

Plot 3

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	6.6	6.6	0	0	0	0	94
20	8.4	15	0	0	0	0	
30	9.7	24.7	2.3	0.4	0.9	0.9	
40	6.6	31.3	1.4	2	2.8	3.7	
50	2.2	33.5	4	4.9	20	23.3	
60	12.3	45.8	3.6	7.3	26	49.6	
70	11.5	57.3	2	7.7	15	65	
80	9.7	67	0.8	4.6	3.7	68.7	
90	9.3	76.3	0.4	1.5	0.6	69.3	

Plot 4

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	3.5	3.5	0	0	0	0	22
20	8.4	11.9	2	0.1	0.2	0.2	
30	10.1	22	2	2.1	4.2	4.4	
40	2.6	24.6	1.3	1.7	2.2	6.6	
50	4	28.6	0.5	2.1	1.1	7.7	
60	3	31.6	1.6	3	4.8	12.5	
70	4.4	36	0.6	3.2	1.9	14.4	
80	3.4	39.4	0.8	3.2	2.6	17	
90	2.5	41.9	0.3	1.6	0.5	17.5	

Plot 14

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	17.2	17.2	0	0	0	0	142
20	11.9	29.1	0.6	0.1	0.1	0.1	
30	8.4	37.5	0.6	0.7	0.4	0.5	
40	8.8	46.3	0.6	1.6	1	1.5	
50	11	57.3	0.8	2.2	1.8	3.3	
60	14.1	71.4	0.7	2.5	1.8	5.1	
70	15	86.4	0.7	2.9	2	7.1	
80	9.7	96.1	0.6	2.7	1.6	8.7	
90	8.8	104.9	0.5	2.2	1.1	9.8	

Plot 18

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	8.4	8.4	2.6	1.1	2.9	2.9	55
20	4.4	12.8	2.1	4	8.4	11.3	
30	7	19.8	1.1	5.5	6	17.3	
40	5.7	25.5	1	6.1	6	23.3	
50	7.9	33.4	0.5	6.7	3.3	26.6	
60	5.3	38.7	1.2	7.3	8.8	35.4	
70	4	42.7	1	7.5	7.5	42.9	
80	6.2	48.9	1	6.2	6.2	49.1	
90	3.3	52.2	0.8	4.5	3.6	52.7	

Plot 24

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	10.1	10.1	0	0	0	0	46
20	5.7	15.8	1.5	0.2	0.3	0.3	
30	7	22.8	1.2	1.7	2	2.3	
40	6.2	29	1.2	3.1	3.7	6	
50	7.5	36.5	1.7	4.7	8	14	
60	6.2	42.7	1.3	6.2	8.1	22.1	
70	5.3	48	0.7	6.6	4.6	26.7	
80	4.8	52.8	0.7	5.8	4.1	30.8	
90	4.8	57.6	0.7	3.9	2.7	33.5	

(3) Plots on severely eroded Lixisols

Plot 16

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	7.9	7.9	0	0	0	0	61
20	5.3	13.2	0	0	0	0	
30	10.6	23.8	1.5	0.6	0.9	0.9	
40	7.5	31.3	1.1	0.6	0.7	1.6	
50	9.7	41	0.8	0.7	0.6	2.2	
60	8.8	49.8	0.8	1	0.8	3	
70	7.9	57.7	0.9	1	0.9	3.9	
80	6.2	63.9	0.8	1	0.8	4.7	
90	6.2	70.1	0.6	0.8	0.5	5.2	

Plot 19

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	4	4	0	0	0	0	72
20	7	11	0	0	0	0	
30	5.7	16.7	1.4	0.1	0.1	0.1	
40	7.5	24.2	1.3	1.8	2.3	2.4	
50	7.9	32.1	1.3	3.3	4.3	6.7	
60	4	36.1	1.3	4.1	5.3	12	
70	5.3	41.4	1.8	4.4	7.9	19.9	
80	3.5	44.9	1.3	4.2	5.5	25.4	
90	2.2	47.1	1.3	3.7	4.8	30.2	

B.1.2 On Vertisols

(1) Plot on slightly eroded Vertisols

Plot 6

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	5.3	5.3	0	0	0	0	0
20	4.8	10.1	0	0	0	0	0
30	5.3	15.4	0	0	0	0	0
40	6.2	21.6	0	0	0	0	0
50	8.8	30.4	0	0	0	0	0
60	6.2	36.6	0	0	0	0	0
70	4.8	41.4	0	0	0	0	0
80	7	48.4	0	0	0	0	0
90	7	55.4	0	0	0	0	0

(2) Plots on moderately eroded Vertisols

Plot 11

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	12.8	12.8	0	0	0	0	39
20	7.9	20.7	0	0	0	0	
30	10.1	30.8	1.6	1.7	2.7	2.7	
40	4.8	35.6	1.3	3.4	4.4	7.1	
50	9.3	44.9	1.1	4.1	4.5	11.6	
60	11	55.9	1.1	4	4.4	16	
70	13.2	69.1	1.1	4.6	5.1	21.1	
80	8.4	77.5	1.1	4.6	5.1	26.2	
90	3.1	80.6	1	4.1	4.1	30.3	

Plot 17

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	5.3	5.3	0	0	0	0	123
20	6.6	11.9	0	0	0	0	
30	6.2	18.1	2	0.5	1	1	
40	6.6	24.7	1.9	2.5	4.8	5.8	
50	6.2	30.9	2.9	4	11.6	17.4	
60	6.2	37.1	2.4	5.3	12.7	30.1	
70	6.2	43.3	2	5.5	11	41.1	
80	8.8	52.1	2.1	5.1	10.7	51.8	
90	3.5	55.6	2	4.5	9	60.8	

(3) Plots on severely eroded Vertisols

Plot 21

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	4	4	0	0	0	0	28
20	4	8	0	0	0	0	
30	4.4	12.4	0	0	0	0	
40	5.3	17.7	0	0	0	0	
50	4.4	22.1	0.7	0.1	0.1	0.1	
60	4	26.1	1	0.6	0.6	0.7	
70	4.4	30.5	1.2	0.9	1.1	1.8	
80	4.4	34.9	0.9	1.1	1	2.8	
90	5.3	40.2	0.7	1	0.7	3.5	

B.1.3 On Cambisols

(1) Plots on slightly eroded Cambisols

Plot 2

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	10.6	10.6	0	0	0	0	7
20	7.1	17.7	0	0	0	0	
30	10.1	27.8	0	0	0	0	
40	11	38.8	0	0	0	0	
50	7.5	46.3	0	0	0	0	
60	7.5	53.8	0.9	0.6	0.5	0.5	
70	6.6	60.4	1	0.8	0.8	1.3	
80	8.8	69.2	1	0.9	0.9	2.2	
90	7.5	76.7	1	0.1	0.1	2.3	

Plot 23

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	4.8	4.8	0	0	0	0	0
20	4.8	9.6	0	0	0	0	0
30	4	13.6	0	0	0	0	0
40	4.8	18.4	0	0	0	0	0
50	4.4	22.8	0	0	0	0	0
60	2.6	25.4	0	0	0	0	0
70	4	29.4	0	0	0	0	0
80	4.4	33.8	0	0	0	0	0
90	5.3	39.1	0	0	0	0	0

(2) Plots on moderately eroded Cambisols

Plot 10

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	6.6	6.6	0	0	0	0	37
20	7	13.6	1.6	0.7	1.1	1.1	
30	6.2	19.8	1.2	2.2	2.6	3.7	
40	8.8	28.6	1.5	2.8	4.2	7.9	
50	5.3	33.9	0.9	3.3	3	10.9	
60	8.4	42.3	1	4.3	4.3	15.2	
70	4.8	47.1	1	4.4	4.4	19.6	
80	7.9	55	0.6	4	2.4	22	
90	5.3	60.3	0.6	3.5	2.1	24.1	

Plot 20

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	6.6	6.6	0	0	0	0	229
20	4.8	11.4	2.1	0.3	0.6	0.6	
30	8.4	19.8	2.3	1.8	4.1	4.7	
40	7	26.8	2.1	2.9	6.1	10.8	
50	6.6	33.4	3.4	4.3	14.6	25.4	
60	7.5	40.9	3.2	5.4	17.3	42.7	
70	8.4	49.3	4.2	6.4	26.9	69.6	
80	4.4	53.7	2.9	5.8	16.8	86.4	
90	5.3	59	2.3	4.7	10.8	97.2	

(3) Plots on severely eroded Cambisols

Plot 1

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	9.3	9.3	0	0	0	0	59
20	5.7	15	0	0	0	0	
30	5.3	20.3	5.1	2.3	11.7	11.7	
40	6.2	26.5	1.9	2.8	5.3	17	
50	6.2	32.7	3	3.9	11.7	28.7	
60	7.5	40.2	1.1	5.3	5.8	34.5	
70	8.4	48.6	2.2	5.3	11.7	46.2	
80	10.6	59.2	0.9	4.3	3.9	50.1	
90	6.2	65.4	0.6	2.4	1.4	51.5	

Plot 5

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	8.4	8.4	0	0	0	0	76
20	4.8	13.2	0	0	0	0	
30	6.2	19.4	1.5	0.4	0.6	0.6	
40	5.7	25.1	2	1.3	2.6	3.2	
50	7	32.1	2.9	2.4	7	10.2	
60	7.5	39.6	1.8	4.7	8.4	18.6	
70	8.8	48.4	1.8	4.9	8.8	27.4	
80	6.6	55	1	3.9	3.9	31.3	
90	6.2	61.2	0.8	2.7	2.2	33.5	

B.1.4 On Fluvisols

(1) Plots on slightly eroded Fluvisols

Plot 9

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	17.2	17.2	0	0	0	0	57
20	21.6	38.8	0	0	0	0	
30	19.8	58.6	0	0	0	0	
40	12.3	70.9	0	0	0	0	
50	17.6	88.5	2.1	0.3	0.6	0.6	
60	18.5	107	2.4	1.1	2.6	3.2	
70	12.3	119.3	3.3	2.5	8.3	11.5	
80	15.9	135.2	2.7	2.2	5.9	17.4	
90	17.6	152.8	1.4	1.5	2.1	19.5	

(2) Plots on moderately eroded Fluvisols

Plot 22

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	18.1	18.1	0	0	0	0	28
20	14.1	32.2	0	0	0	0	
30	11	43.2	0	0	0	0	
40	14.1	57.3	0.9	0.8	0.7	0.7	
50	11.9	69.2	0.9	3.8	3.4	4.1	
60	17.2	86.4	1.8	4.5	8.1	12.2	
70	13.7	100.1	1	4.5	4.5	16.7	
80	11.5	111.6	0.4	4.1	1.6	18.3	
90	11	122.6	0.4	2.5	1	19.3	

B.1.5 On severely eroded Leptosols

Plot 12

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	7.9	7.9	0	0	0	0	38
20	3.1	11	0.3	0.6	0.2	0.2	
30	4.1	15.1	0.2	2.3	0.5	0.7	
40	3.1	18.2	0.2	3.3	0.7	1.4	
50	2.2	20.4	0.2	3.8	0.8	2.2	
60	1.8	22.2	0.2	4.5	0.9	3.1	
70	1.8	24	0.2	4.5	0.9	4	
80	1.3	25.3	0.2	4.2	0.8	4.8	
90	1.8	27.1	0.1	3.5	0.4	5.2	

B.1.6 On Planosols

(1) Plot on slightly eroded Planosols

Plot 15

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	15.9	15.9	0	0	0	0	92
20	8.4	24.3	1.4	0.3	0.4	0.4	
30	8.4	32.7	1.4	2.7	3.8	4.2	
40	9.7	42.4	1.3	3.6	4.7	8.9	
50	6.6	49	1.3	4.4	5.7	14.6	
60	8.4	57.4	0.9	4.5	4.1	18.7	
70	7.5	64.9	1	4.6	4.6	23.3	
80	8.4	73.3	0.8	3.9	3.1	26.4	
90	7	80.3	0.6	3.2	1.9	28.3	

(2) Plot on moderately eroded Planosols

Plot 13

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	12.8	12.8	0	0	0	0	66
20	7.9	20.7	1.5	0.2	0.3	0.3	
30	10.1	30.8	1.4	2	2.8	3.1	
40	8.4	39.2	1.1	3	3.3	6.4	
50	9.7	48.9	1.4	4.2	5.9	12.3	
60	7.1	56	1.4	5.6	7.8	20.1	
70	9.7	65.7	0.7	5.8	4.1	24.2	
80	7.5	73.2	0.5	4.5	2.3	26.5	
90	8.8	82	0.6	3.1	1.9	28.4	

(3) Plots on severely eroded Planosols

Plot 8

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	6.6	6.6	0	0	0	0	107
20	6.6	13.2	1.7	0.5	0.9	0.9	
30	4.4	17.6	2	1.1	2.2	3.1	
40	2.6	20.2	2.3	2.5	5.7	8.8	
50	2	22.2	1.8	3.3	5.9	14.7	
60	2.6	24.8	3.4	4.7	16	30.7	
70	1.5	26.3	2.5	5	13	43.2	
80	4	30.3	0.8	3.7	3	46.2	
90	4.4	34.7	1.1	2.5	2.7	48.9	

Plot 25

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	4.4	4.4	0	0	0	0	160
20	4	8.4	1.9	0.6	1.1	1.1	
30	3.1	11.5	2.3	3.2	7.4	8.5	
40	2.6	14.1	2.8	3.2	9	17.5	
50	4	18.1	2.4	5.1	12.2	29.7	
60	2.6	20.7	2.6	6.1	15.9	45.6	
70	3.5	24.2	2.9	6.1	17.7	63.3	
80	4.4	28.6	1.7	5	8.5	71.8	
90	2.6	31.2	1.7	4	6.8	78.6	

B.2 EROSION PARAMETERS IN RAIN 3

B.2.1 On Lixisols

(1) Plot on slightly eroded Lixisols

Plot 7

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	12.8	12.8	0.7	1.2	0.8	0.8	42
20	8.8	21.6	0.4	3.5	1.4	2.2	
30	12.3	33.9	0.6	5.4	3.2	5.4	
40	12.8	46.7	0.6	5.4	3.2	8.6	
50	9.7	56.4	0.6	6.2	3.7	12.3	
60	13.2	69.6	0.7	8.3	5.8	18.1	
70	11.5	81.1	0.4	8.6	3.4	21.5	
80	10.1	91.2	0.3	6.7	2	23.5	
90	11.5	102.7	0.3	4.3	1.3	24.8	

(2) Plots on moderately eroded Lixisols

Plot 3

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	10.6	10.6	0.8	0.1	0.1	0.1	40
20	4	14.6	0.8	3	2.4	2.5	
30	4	18.6	0.7	4.6	3.2	5.7	
40	2.2	20.8	0.8	4.6	3.7	9.4	
50	4.8	25.6	0.7	5.2	3.6	13	
60	6.2	31.8	0.6	6.6	4	17	
70	10.6	42.4	0.3	6.7	2	19	
80	10.6	53	0.2	5.5	1.1	20.1	
90	11	64	0.3	3.5	1	21.2	

Plot 4

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	14.1	14.1	2.6	0.8	2.1	2.1	88
20	5.3	19.4	1.6	2.8	4.5	6.6	
30	6.2	25.6	1.4	4.4	6.1	12.7	
40	3.5	29.1	2.3	4.4	10.1	22.8	
50	6.6	35.7	1.8	4.4	7.9	30.7	
60	15.9	51.6	2.5	5.5	13.7	44.4	
70	14.1	65.7	2.1	6.6	13.8	58.2	
80	12.8	78.5	1.8	4.8	8.6	66.8	
90	12.8	91.3	3.2	2.6	8.3	75.1	

Plot 14

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	9.7	9.7	0.9	4	3.6	3.6	226
20	8.4	18.1	1.9	5.3	10.1	13.7	
30	11.5	29.6	1.3	6.8	8.8	22.5	
40	8.4	38	0.6	6.8	4.1	26.6	
50	11.5	49.5	0.8	7.4	5.9	32.5	
60	16.7	66.2	1.2	9	10.8	43.3	
70	11	77.2	1.2	8.9	10.7	54	
80	8.4	85.6	1.5	6.6	9.9	63.9	
90	5.3	90.9	1.2	4	4.8	68.7	

Plot 18

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	5.3	5.3	0.5	3.4	1.7	1.7	34
20	5.3	10.6	0.6	5.1	3.1	4.8	
30	5.7	16.3	0.3	7.5	2.3	7.1	
40	5.3	21.6	0.4	7.5	3	10.1	
50	5.7	27.3	0.5	8.4	4.2	14.3	
60	7	34.3	0.5	10.3	5.2	19.5	
70	4.4	38.7	0.7	10.3	7.2	26.7	
80	5.3	44	0.3	7.7	2.3	29	
90	5.3	49.3	0.3	4.7	1.4	30.4	

Plot 24

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	5.7	5.7	1	3	3	3	156
20	4	9.7	1.2	5.9	7.1	10.1	
30	7	16.7	1.2	8.1	9.7	19.8	
40	4.4	21.1	1.1	8.1	8.9	28.7	
50	7.5	28.6	1.8	9.2	16.6	45.3	
60	6.6	35.2	2.2	11	24.9	70.2	
70	7	42.2	2.7	11	30.5	100.7	
80	4	46.2	1.7	8	13.6	114.3	
90	2.6	48.8	1.2	4.6	5.5	119.8	

(3) Plots on severely eroded Lixisols

Plot 16

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	7.5	7.5	0.7	0.7	0.5	0.5	326
20	7.5	15	1.2	1.3	1.6	2.1	
30	6.6	21.6	1.2	2.2	2.6	4.7	
40	9.7	31.3	1.6	2.5	4	8.7	
50	7.9	39.2	8.9	4	35.6	44.3	
60	14.1	53.3	6	6.2	37.2	81.5	
70	9.7	63	9.1	6.2	56.4	138	
80	9.7	72.7	1.7	5.5	9.4	147	
90	8.4	81.1	1.5	3.3	4.9	152	

Plot 19

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	4.4	4.4	1.2	1.4	1.7	1.7	159
20	2.6	7	1.5	5.2	7.8	9.5	
30	3.1	10.1	1.4	6.3	8.8	18.3	
40	3.5	13.6	1.7	6.3	10.7	29	
50	4.4	18	2	7.3	14.6	43.6	
60	4.8	22.8	1.6	9.3	14.9	58.5	
70	3.5	26.3	1.5	9.3	14	72.5	
80	2.6	28.9	1	7.1	7.1	79.6	
90	5.3	34.2	1	4	4	83.6	

B.2.2 On Vertisols

(1) Plot on slightly eroded Vertisols

Plot 6

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	20	20	0	0	0	0	0
20	16.3	36.3	0	0	0	0	0
30	4.8	41.1	0	0	0	0	0
40	9.3	50.4	0	0	0	0	0
50	5.3	55.7	0	0	0	0	0
60	4	59.7	0	0	0	0	0
70	4.9	64.6	0	0	0	0	0
80	5.3	69.9	0	0	0	0	0
90	4	73.9	0	0	0	0	0

(2) Plots on moderately eroded Vertisols

Plot 11

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	4.8	4.8	0.6	1.7	1	1	48
20	6.2	11	0.9	4.5	4.1	5.1	
30	6.6	17.6	0.5	5.6	2.8	7.9	
40	7.5	25.1	0.7	5.6	3.9	11.8	
50	5.7	30.8	0.7	6.3	4.4	16.2	
60	7.5	38.3	0.9	7.8	7	23.2	
70	5.3	43.6	1.2	7.8	9.4	32.6	
80	7.9	51.5	0.4	6.4	2.6	35	
90	4	55.5	0.3	4.6	1.4	2 36.6	

Plot 17

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	16.3	16.3	2.7	1.5	4.1	4.1	431
20	6.2	22.5	2.6	4.8	12.5	16.6	
30	9.3	31.8	4.8	6.6	31.7	48.3	
40	5.7	37.5	3.8	7.5	28.5	76.8	
50	5.3	42.8	4.9	7.5	36.8	114	
60	15	57.8	7.9	7.5	59.3	173	
70	5.3	63.5	5.5	10.7	58.9	232	
80	4	67.5	5.8	8	46.4	278	
90	4	71.5	5.3	4.5	23.9	302	

(3) Plot on severely eroded Vertisols

Plot 21

Time interval (minute)	Incremental splash (g/m²)	Cumulative splash (g/m²)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m²)	Cumulative soil wash (g/m²)	Total soil loss (g/m²)
10	5.3	5.3	1.3	1.3	1.7	1.7	613
20	5.5	10.8	1.7	5	8.5	10.2	
30	4.8	15.6	4.2	6.8	28.6	38.8	
40	5.7	21.3	4.8	7.4	35.5	74.3	
50	5.7	27	8.7	8.5	74	148	
60	5.3	32.3	8.7	9.8	85.3	234	
70	7	39.3	11	10.9	124	358	
80	6.6	45.9	4.8	7.5	36	394	
90	7	52.9	7	4.5	31.5	425	

B.2.3 On Cambisols

(1) Plots on slightly eroded Cambisols

Plot 2

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	9.3	9.3	0	0	0	0	47
20	13.2	22.5	1.6	0.9	1.4	1.4	
30	14.7	37.2	2.2	3	6.6	8	
40	4.8	42	1.9	3.1	5.9	13.9	
50	4.8	46.8	1.7	3.3	5.6	19.5	
60	5.3	52.1	1.5	3.5	5.3	24.8	
70	19.4	71.5	1	5	5	29.8	
80	16.7	88.2	0.8	3.6	2.9	32.7	
90	5.3	93.5	1.4	1	1.4	34.1	

Plot 23

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	5.3	5.3	0	0	0	0	33
20	5.3	10.6	0	0	0	0	
30	4	14.6	0	0	0	0	
40	5.3	19.9	0	0	0	0	
50	5.3	25.2	4.2	0.4	1.7	1.7	
60	7.5	32.7	2.3	1.8	4.1	5.8	
70	6.2	38.9	1.3	2.6	3.4	9.2	
80	8.8	47.7	0.7	2	1.4	10.6	
90	4.4	52.1	0.5	0.4	0.2	10.8	

(2) Plots on moderately eroded Cambisols

Plot 10

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	4.4	4.4	0.3	2.6	0.8	0.8	62
20	4	8.4	0.4	4.4	1.8	2.6	
30	4.4	12.8	0.6	5.4	3.2	5.8	
40	4.4	17.2	0.5	5.5	2.8	8.6	
50	3.5	20.7	0.3	6.1	1.8	10.4	
60	3.5	24.2	0.8	7.7	6.2	16.6	
70	4	28.2	0.6	4.4	4.4	21	
80	3.1	31.3	0.7	5.9	4.1	25.1	
90	3.1	34.4	0.2	4.3	0.9	26	

Plot 20

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	4.4	4.4	1.3	2.4	3.1	3.1	710
20	6.6	11	2.8	5.8	16.2	19.3	
30	8.4	19.4	3	7.7	23.1	42.4	
40	7	26.4	10.2	7.7	78.5	120.9	
50	5.7	32.1	4.1	9.2	37.7	158.6	
60	9.3	41.4	12.8	11.3	145	303.2	
70	8.8	50.2	13.7	11.1	152	455.3	
80	7.5	57.7	8.8	7.9	69.5	524.8	
90	4	61.7	7.1	4.5	32	556.8	

(3) Plots on severely eroded Cambisols

Plot 1

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	7.5	7.5	1.5	0.8	1.2	1.2	157
20	5.3	12.8	3.8	2.9	11	12.2	
30	11.5	24.3	5.2	4.4	22.9	35.1	
40	12.3	36.6	2.4	4.4	10.6	45.7	
50	18.5	55.1	2.8	5.3	14.8	60.5	
60	8.4	63.5	1.7	8.4	14.3	74.8	
70	15.4	78.9	4.8	8.9	42.7	118	
80	16.4	95.3	4.3	5.9	25.4	143	
90	11	106.3	1.4	3.3	4.6	148	

Plot 5

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	8.4	8.4	0.7	0.7	0.5	0.5	231
20	5.7	14.1	0.4	3.5	1.4	1.9	
30	7	21.1	3	4.7	14.1	16	
40	4.8	25.9	2	5	10	26	
50	14.1	40	2.3	5.2	12	38	
60	11	51	3.4	7.4	25.2	63.2	
70	9.7	60.7	6.2	7.6	47.1	110.3	
80	8.8	69.5	3.1	5.8	18	128.3	
90	3.5	73	2.6	3.4	8.8	137.1	

B.2.4 On Fluvisols

(1) Plot on slightly eroded Fluvisols

Plot 9

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	21.9	21.9	0	0	0	0	82
20	10.1	32	1.7	0.5	0.9	0.9	
30	7.1	39.1	1.7	1.9	3.2	4.1	
40	14.5	53.6	3.2	2.2	7	11.1	
50	6.6	60.2	1.5	3.2	4.8	15.9	
60	17.6	77.8	1.5	5	7.5	23.4	
70	18.1	95.9	1.8	5	9	32.4	
80	11.9	107.8	0.9	3.9	3.5	35.9	
90	8.4	116.2	2.4	1.5	3.5	39.4	

(2) Plot on moderately eroded Fluvisols

Plot 22

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	6.6	6.6	0.4	1.7	0.7	0.7	46
20	6.2	12.8	0.3	4.3	1.3	2	
30	11.5	24.3	0.6	6.7	4	6	
40	7.5	31.8	0.6	7.1	4.3	10.3	
50	14.1	45.9	0.7	7.4	5.2	15.5	
60	25.1	71	0.6	9.2	5.5	21	
70	12.3	83.3	0.8	9.7	7.8	28.8	
80	6.2	89.5	0.7	7.3	5.1	33.9	
90	3.1	92.6	0.6	4.5	2.7	36.6	

B.2.5 On severely eroded Leptosols

Plot 12

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	3.5	3.5	0.2	1.3	0.3	0.3	48
20	1.8	5.3	0.2	4.4	0.9	1.2	
30	1.8	7.1	0.2	5.4	1.1	2.3	
40	2.2	9.3	0.1	5.4	0.5	2.8	
50	1	10.3	0.1	5.6	0.6	3.4	
60	1.3	11.6	0.2	6.7	1.3	4.7	
70	1	12.6	0.1	6.6	0.7	5.4	
80	1	13.6	0.1	5.6	0.6	6	
90	1	14.6	0.1	4.5	0.5	6.5	

B.2.6 On Planosols

(1) Plot on slightly eroded Planosols

Plot 15

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	9.7	9.7	1.1	1.4	1.5	1.5	220
20	5.3	15	1.6	7.4	11.8	13.3	
30	5.3	20.3	1.6	6.8	10.9	24.2	
40	5.3	25.6	1.5	6.8	10.2	34.4	
50	9.7	35.3	1.5	7	10.5	44.9	
60	6.6	41.9	2	7.5	15	59.9	
70	7.5	49.4	2.4	7.5	18	77.9	
80	5.3	54.7	2.5	6.2	15.5	93.4	
90	4.8	59.5	1.5	4.8	7.2	100.6	

(2) Plot on moderately eroded Planosols

Plot 13

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	6.6	6.6	0.8	3.3	2.6	2.6	179
20	9.7	16.3	1	5.5	5.5	8.1	
30	9.7	26	0.9	7.3	6.6	14.7	
40	7.5	33.5	1.1	7.5	8.3	23	
50	8.4	41.9	0.7	9.1	6.4	29.4	
60	19	60.9	1.9	9.9	18.8	48.2	
70	11.5	72.4	1.8	10.3	18.5	66.7	
80	9.3	81.7	0.4	7.7	3.1	69.8	
90	6.6	88.3	0.5	4.6	2.3	72.1	

(3) Plots on severely eroded Planosols

Plot 8

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	8.8	8.8	0.6	0.1	0.1	0.1	153
20	4.4	13.2	0.4	1.1	0.4	0.5	
30	2.6	15.8	2.5	5.5	13.8	14.3	
40	6.6	22.4	1.3	6	7.8	22.1	
50	5.3	27.7	1.5	6	9	31.1	
60	2.5	30.2	1.4	7.3	10.2	41.3	
70	4	34.2	1.5	7.5	11.3	52.6	
80	2.2	36.4	0.8	6	4.8	57.4	
90	4	40.4	0.4	2.2	0.9	58.3	

Plot 25

Time interval (minute)	Incremental splash (g/m^2)	Cumulative splash (g/m^2)	Sediment concentration (g/l)	Incremental runoff (mm)	Incremental soil wash (g/m^2)	Cumulative soil wash (g/m^2)	Total soil loss (g/m^2)
10	2.6	2.6	1.1	3.4	3.7	3.7	409
20	2.2	4.8	0.8	5.6	4.5	8.2	
30	2.6	7.4	2	7.1	14.2	22.4	
40	1.3	8.7	2.1	7.1	14.9	37.3	
50	1.3	10	2.9	8.7	25.2	62.5	
60	2.6	12.6	4.8	11	52.8	115.3	
70	2.6	15.2	5.7	11.4	65	180.3	
80	2.2	17.4	8.3	7.8	64.7	245	
90	1.3	18.7	6	4.5	27	272	

ANNEX C
TOPSOIL PROPERTIES OF THE EXPERIMENTAL PLOTS

C.1 MORPHOLOGICAL AND PHYSICAL PROPERTIES

Soil types	Ec	Plot	Ad	St	Cl	Sif	Sic	Saf	Sac	Cp	Bd	W2	W3
Lixisols	1*	7	28	10	7	7	14	33	40	1	1.5	7	16
	2*	3	12	13	10	6	12	36	35	36	1.5	11	9
		4	13	13	13	14	9	31	34	17	1.6	7	11
		14	14	10	4	2	9	29	57	3	1.6	2	10
		18	10	10	7	4	11	30	48	12	1.6	3	10
		24	15	33	15	5	8	37	35	22	1.6	7	16
	3*	16	5	32	30	8	6	20	37	8	1.6	3	18
		19	3	31	17	8	17	27	28	23	1.7	3	18
Vertisols	1*	6	10	44	29	13	15	24	30	38	1.3	19	18
	2*	11	15	33	19	5	15	32	28	7	1.4	16	16
		17	12	41	29	7	5	41	19	19	1.3	11	21
	3*	21	3	41	29	11	16	24	18	19	1.5	11	21
Cambisols	1*	2	5	32	5	5	7	33	50	29	1.7	9	15
		23	12	42	31	7	15	25	19	7	1.4	7	20
	2*	10	40	10	7	5	18	32	39	6	1.6	6	15
		20	25	41	26	11	15	30	19	14	1.5	6	25
	3*	1	7	10	5	3	13	36	43	9	1.4	7	11
		5	15	32	23	8	13	36	21	31	1.6	12	17
Fluvisols	1*	9	35	10	5	4	4	56	26	0	1.5	15	13
	2*	22	90	10	7	4	13	47	29	8	1.5	3	18
Leptosols	3*	12	6	22	9	5	4	31	50	59	1.8	2	15
Planosols	1*	15	54	10	7	7	17	39	31	0	1.6	6	14
	2*	13	21	10	10	6	16	24	43	10	1.5	2	12
	3*	8	3	41	24	11	17	20	27	11	1.7	2	15
		25	30	10	16	8	10	35	31	47	1.6	6	17

where:
Ec is erosion classes; 1* is slightly eroded soil class; 2* is moderately eroded soil class; 3* is severely eroded soil class; Ad is depth to B horizon or bed rock in cm; St is structure; Cl is clay content in %; Sif is fine silt content in %; Sic is coarse silt content in %; Saf is fine sand content in %; Sac is coarse sand in %; Cp is coarse particle content in %; Bd is bulk density in Mg m^{-3} ; W2 is initial soil moisture content before rain 2, in weight %; and w3 is initial soil moisture content before rain 3, in weight %.

C.2 CHEMICAL PROPERTIES

Soil types	Ec	Plot	O.M	N	P	Fe	Ca	Mg	K	Na	pH
Lixisols	1*	7	0.67	0.04	26	0.99	2.91	1.45	12.6	13.4	6.8
	2*	3	1.43	0.08	3	1.40	3.13	1.65	2.59	4.21	6.3
		4	1.12	0.07	2	1.39	3.26	2.28	2.46	4.16	6.5
		14	0.12	0.04	3	0.51	1.13	0.81	0.15	0.10	7.3
		18	0.31	0.05	4	0.95	21	6.95	0.36	0.71	6.5
		24	1.31	0.06	2	1.34	4.90	2.28	0.15	0.17	6.8
	3*	16	0.07	0.06	1	2.11	5.77	3	0.10	0.10	5.8
		19	0.83	0.06	4	1.51	4.90	2.28	0.42	0.53	6.5
Vertisols	1*	6	0.98	0.05	4	1.44	14.14	6.32	2.71	4.52	7.7
	2*	11	0.52	0.06	23	1.48	13.35	1.48	0.37	0.36	8.1
		17	0.43	0.06	4	1.29	15.48	3.99	1.01	1.04	7.8
	3*	21	1.38	0.09	12	1.54	16.32	4.41	0.42	0.54	8.5
Cambisols	1*	2	0.83	0.05	22	1.13	2.10	0.97	2.53	3.96	7.2
		23	1.72	0.08	3	1.63	16.46	4.70	0.11	0.18	7.3
	2*	10	0.74	0.08	45	1.05	3.88	1.78	2.79	4.14	7.1
		20	0.55	0.04	7	1.66	12.31	3.16	1.01	1.36	8.0
	3*	1	0.69	0.06	6	0.84	2.10	0.97	2.43	4.33	7.5
		5	0.91	0.06	4	2.35	12.31	4.66	2.61	4.17	7.3
Fluvisols	1*	9	0.60	0.07	38	1.12	3.39	1.62	2.07	4.57	8.1
	2*	22	1.28	0.07	16	0.83	3.72	5.33	0.31	0.26	6.8
Leptosols	3*	12	0.72	0.09	43	2.13	6.26	1.65	0.42	0.49	6.6
Planosols	1*	15	0.41	0.05	4	1.12	2.91	0.65	0.41	0.10	6.0
	2*	13	0.55	0.06	4	1.10	2.42	0.97	0.15	0.10	6.4
	3*	8	0.79	0.09	2	2.14	5.27	5.44	2	4.61	6.0
		25	1.72	0.08	3	1.25	5.39	2.77	0.10	0.17	6.8

where:

Ec is erosion classes; 1* is slightly eroded soil class; 2* is moderately eroded soil class; 3* is severely eroded soil class; O.M is organic matter content in %; N is nitrogen content in %; P is phosphorus content in cmol (+) kg^{-1} of soil; Fe is free iron content in %; Ca is calcium content in cmol (+) kg^{-1} of soil; Mg is magnesium content in cmol (+) kg^{-1} of soil; K is potassium content in cmol (+) kg^{-1} of soil; Na is sodium content in cmol (+) kg^{-1} of soil; and pH is the degree of acidity (or alkalinity) measured in 1:2.5 soil/water suspension.

ANNEX D
SOIL STRUCTURE CODE DETERMINATION

Code of different structure types	Code of different structure sizes		
	Coarse: 3	Medium: 2	Fine: 1
Prismatic: 4	43	42	41
Columnar: 3	33	32	31
Sub-angular blocky: 2	23	22	21
Massive: 1	13	12	11